CA8160 Georgia Institute of Technology C.1
Office of Contract Administration 28-JAN-1998 1·
OCA PAD AMENDMENT - PROJECT HEADER INFORMATION

Document Header Id #: 39761 ACT:
Project #: E-25-L63 Cost share #: E-25-328 Rev #: 3
Center #: 10/24-6-R0083-0A0 Center shr #: 10/22-1-F0083-0A0
OCA file #: Project type: RES

Contract #: N00014-96-1-1195 Mod #: P00002 Award type: GRANT
Prime #: Contract entity: GTRC
Contract type: CRNF

CFDA: 12.300
PE #: N/A

Project unit: MECH ENGR Unit code: 28
Project director(s):
PDPI- ZHOU M MECH ENGR (404)894-3294

Sponsor : NAVY/OFC OF NAVAL RESEARCH
Division Id: 103 / 3314
Award period: 01-AUG-1996 to 31-JUL-1998 (performance) 31-JUL-1998 (reports)

Sponsor amount	New this change	Total to date
Contract value:	0.00	92,296.00
Funded:	38,296.00	92,296.00
Cost sharing amount:	0.00	26,512.00

Does subcontracting plan apply?

Title: DYNAMIC FAILURE BEHAVIOR OF NAVAL STRUCTURAL STEELS

PROJECT ADMINISTRATIVE DATA

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Security class (U,C,S,TS): U
Defense priority rating : N/A

ONR resident rep is ACO (Y/N): Y
Supplemental sheet: ONR

Equipment title vests with: G

Administrative comments -
Adds incremental funding of $38,296.

PROJECT CLOSEOUT - NOTICE

Closeout Notice Date 12-NOV-1998

Project Number E-25-L63 Doch Id 39761

Center Number 10/24-6-R0083-0A0

Project Director ZHOU, MIN

Project Unit MECH ENGR

Sponsor NAVY/OFC OF NAVAL RESEARCH

Division Id 3314

Contract Number N00014-96-1-1195 Contract Entity GTRC

Prime Contract Number

Title DYNAMIC FAILURE BEHAVIOR OF NAVAL STRUCTURAL STEELS

Effective Completion Date 30-SEP-1998 (Performance) 30-SEP-1998 (Reports)

Closeout Action:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory and Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments

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Distribution Required:	
Project Director/Principal Investigator	Y
Research Administrative Network	Y
Accounting	Y
Research Security Department	N
Reports Coordinator	Y
Research Property Team	Y
Supply Services Department/Procurement	Y
Georgia Tech Research Corporation	Y
Project File	Y

NOTE: Final Patent Questionnaire sent to PDPI

E.25.263
1

A Progress Report for the Project

DYNAMIC FAILURE BEHAVIOR OF NAVAL STRUCTURAL STEELS

Min Zhou
Georgia Institute of Technology

August 1, 1996 - June 30, 1997

Summary:

The objective of this research is to evaluate the factors that determine the dynamic shear failure resistance of structural metals such as HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V. The project began on August 1, 1996. So far, our experimental investigation has focused on

(1) characterizing the response of constitutive behavior of these materials under dynamic uniaxial compression over the strain rate region of 10^2 to 10^4 s^{-1},
(2) assessing the dynamic shear failure resistance of these materials.

The experiments results showed that

(1) the materials exhibit significant ductility under the conditions tested;
(2) despite their significantly different static properties (such as yield strength), chemical compositions and heat treatment, the steels (HY-80, HY-100, HSLA-80, HSLA-100, and 4340) have very similar dynamic constitutive behaviors in the strain rate range of 10^2 - 10^4 s^{-1};
(3) the steels are relatively rate-insensitive in this strain rate range while the titanium alloy (Ti-6Al-4V) shows much stronger rate-sensitivity in the same strain rate regime;
(4) in spite of its higher rate-sensitivity, Ti-6Al-4V is more susceptible to shear banding and rupture than the steels. This inconsistent with the fact that strong rate-sensitivity enhances resistance to localization. This result suggests other factors dominate the failure process under the conditions analyzed;
(5) there is a relatively large variation in the shear failure resistance among the steels, as measured by the shapes of stress strain curves and the critical shear strain for failure;
(6) it seems that rupture inside shear bands is an important part of the failure process that should to be considered in evaluating failure. Analysis accounting for it is not available at this time.

Experiments:

<u>1. Constitutive analysis:</u> The configuration of the split-Hopkinson bar compression experiment used is shown in Fig. 1. This experiment subjects materials to dynamic loading at strain rates between 10^2 to 10^4 s^{-1}, under conditions of uniaxial compression states of stress.

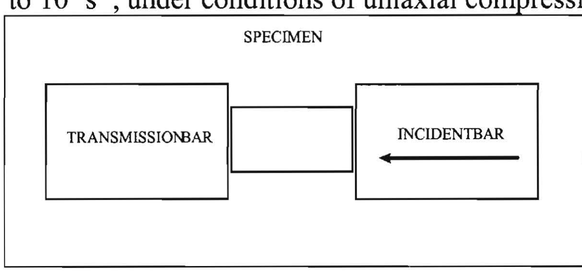

Fig. 1 Dynamic Compression Experiment

2. Dynamic shear failure experiment: This experiment uses a hat-shaped specimen and is conducted on a split Hopkinson compression bar. The compression loading causes intense shear deformation in the ligament of the specimen. The maximum amount of deformation (Δ) permitted is controlled by using stoppers of different thicknesses, therefore allowing the deformation and failure to be "frozen" at different stages of development of microscopic analyses. The configuration of the specimen is shown in Fig. 3.

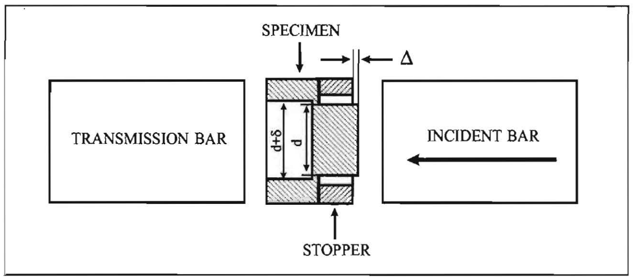

Fig. 2 Dynamic shear failure experiment using a hat specimen

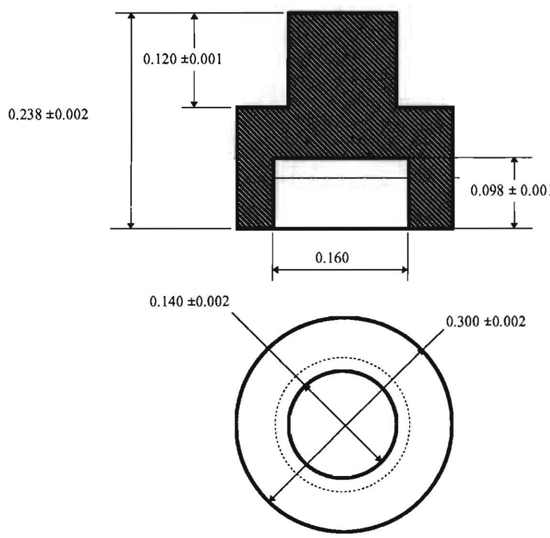

Fig. 3 Hat-shaped Specimen for Shear Failure Analysis

Results:

1. <u>Constitutive response:</u>

The stress-strain response of the materials at a nominal strain rate of $2.5\times10^3\ s^{-1}$ are shown in Fig. 4. The curves indicate similar behavior for the steels and much higher flow stresses for Ti-6Al-4V. Also, the precipitous drop in stress for this material indicates for formation of shear bands which are not observed in the steels.

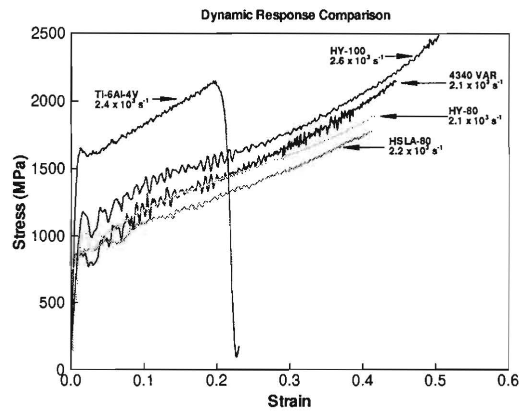

Fig. 4 Constitutive Behavior of the materials Analyzed

2. Shear Failure response:

Shear failure experiments have been conducted on the materials using stopper thickness values between 2-2.9 mm. Shear bands at various stages of development between initiation and eventual rupture have been captured in specimens. The corresponding shear stress-strain curves showing the evolution of the stress carrying capacities of the materials have been recorded. A set of curves for HY-80 are shown in Fig. 5. Comparisons of curves for different materials are shown in Fig. 6 for a stopper thickness of 2.6 mm and Fig. 7 for a stopper thickness of 2.28 mm. The drops in stress signifies the loss of stress carrying capacities and the subsequent increases indicate contact with the stopper rings, therefore, end of shear deformation in the materials. It is clear that Ti-6Al-4V is loses its stress-carrying capacities at a much smaller strain level than the steels. Also, there is a large variation in the shear failure resistance of the steels.

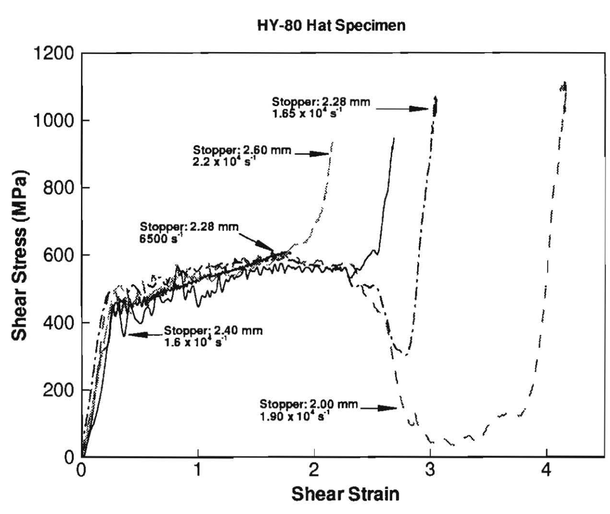

Fig. 5 Shear Stress-strain Curves for HY-80 Steel

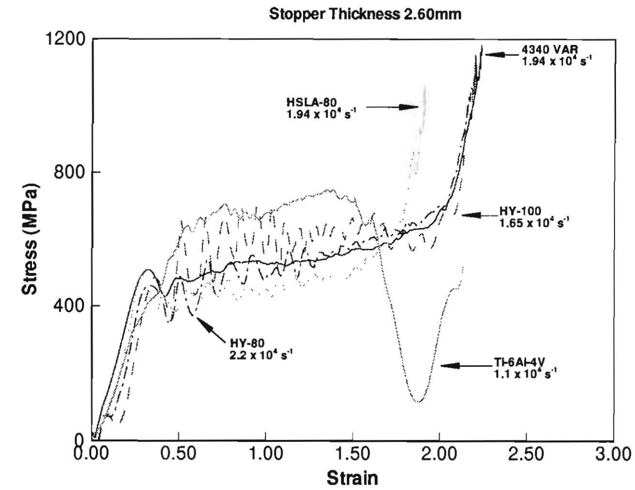

Fig. 6 A comparison of Shear Stress-strain Curves for Different materials (stopper thickness: 2.60 mm)

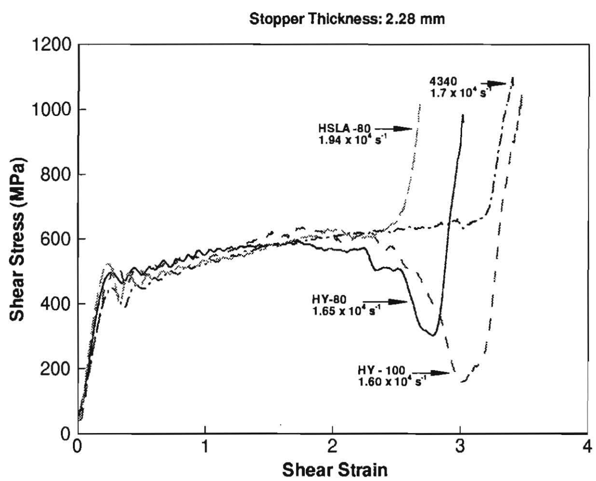

Fig. 7 A comparison of Shear Stress-strain Curves for Different materials (stopper thickness: 2.28 mm)

3. Microscopic characterization

Optical and scanning electron microscopy have been used to analyze the morphology of shear bands and the ductile rupture inside them. It is found that the eventual rupture pays an important role in affecting the progression of shear failure. The microscopic morphology of the shear band and fracture path in a HY-80 specimen is shown in Fig. 8.

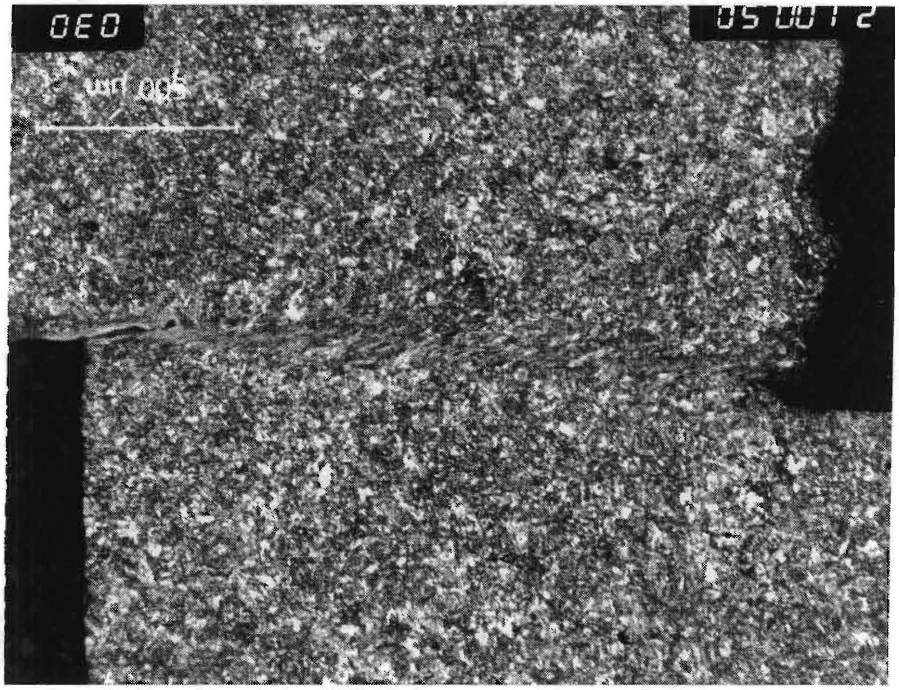

Fig. 8 Shear band in a HY-80 Specimen (stopper thickness: 2.4 mm)

Current Activity:

We are continuing our research in the following areas:

(1) Finite element simulation and modeling of the shear failure process. The modeling is conducted using fully dynamic finite element calculations that account for inertia, finite deformation kinematics, strain rate hardening, thermal softening and heat conduction.

(2) We plan to conduct penetration experiments on the materials to verify our understanding the shear failure resistance.

ONR GRANT INFORMATION

1. **Project Title:** Dynamic Failure Behavior of Naval Structural Steels

2. **Grant No.:** N00014-96-1-1195

3. **R&T No.:** 96PR07524-00

4. **PI Name:** Min Zhou

Institution: Georgia Tech Research Corporation/Georgia Institute of Tech.
Address: 400 Tenth Street
Telephone No.: (404) 894-3294
Fax No.: (404) 894-8336
E-mail Address: min.zhou@me.gatech.edu

5. **Duration of Current Grant:** August 1, 1996 to July 31, 1998

   Start Date: August 1, 1996
   End Date: July 31, 1998

6. **Technical Objective:**

The objective of this project is to analyze and characterize the shear failure behavior of naval structural steels HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V under dynamic conditions. The effort focuses on the evolution of the load-carrying capacity of these materials during shear band development and associated microscopic changes. This effort provides an assessment of the relative resistance to failure and yields important data for designers of naval vessels.

7. **Technical Approach:**

Experimental testing and numerical analysis are used. In the experimental part, a compression Kolsky bar apparatus is used to achieve well-controlled dynamic shear loading coupled with different levels of hydrostatic pressure. In the numerical part, finite element simulations is used to delineate and characterize the influence of different combinations of material properties on shear banding and dynamic impact failure. The materials analyzed are all in the as-received condition from manufacturers. Their properties meet 'military specification' for these materials.

8. **Recent Accomplishments:**

a) material response analysis showed that (1) despite their significantly different static properties (such as yield strength), chemical compositions and heat treatment, the steels (HY-80, HY-100, HSLA-80, HSLA-100, and 4340) have very similar dynamic constitutive behaviors in the strain rate range of 10^2 - 10^4 s^{-1}; (2) the steels are relatively rate-insensitive in this strain rate range; (3) the titanium alloy (Ti-6Al-4V) shows much stronger rate-sensitivity in the same strain rate regime;
b) in spite of its higher rate-sensitivity, Ti-6Al-4V is more susceptible to shear banding and rupture than the steels;
c) there is a relatively large variation in the shear failure resistance among the steels, as measured by the shapes of stress strain curves and the critical shear strain for failure;
d) it seems that rupture inside shear bands is an important part of the failure process that should to be considered in evaluating failure. Analysis accounting for it is not available at this time.

9. **Planned Activities:**

a) we have completed most of our experiments on the constitutive and shear failure analyses. One manuscript for publication in *J. Mech. Phys. Solids* is being prepared;
b) we plan to conduct finite element simulations of the failure experiments and finalize the assessment of the failure resistance of the materials;
c) we plan to run penetration experiments on the materials in validating our assessment. The experiments will emphasize time-resolved measurement of velocity using a VISAR system.

10. **Uniqueness:**

The uniqueness of this research is that (1) it investigates a form of failure in materials that are of direct interest to the navy; and (2) a series of metal alloys are used in a systematic comparison.

11. **Navy Relevance and Impact:**

The structural materials analyzed are military-specified metals used by the navy for ships and vessels. These materials are also analyzed by the Naval Surface Warfare Center in MD. The data and results that can be used by structural designers directly. Also the information obtained provides guidance for the development and choice of more failure-resistant materials.

12. **Interactions/collaborations with other ONR PIs:**

We have been working with Professors Ares J. Rosakis and G. Ravichandran at Caltech. Our efforts are coordinated in that the materials used in our respective projects have both difference and overlap. The common materials used (HY-100 and HSLA-100) allow us to compare our separate results and establish mutually reinforcing data. We also have regular discussions and exchange of data.

13. **Interactions/collaborations with Navy Labs:**

We have been interacting with Dr. Robert DeNale of the Naval Surface Warfare Center in West Bethesda, MD. Data and results in our research are being shared.

14. **Interactions/collaborations with Industry:**

15. **Transitions (Accomplishments being used by others, esp. Navy/Govt. labs or industry)**

The interactions with the NSWC allow us to provide the data obtained to the naval lab.

16. **Recent awards, honors:**

17. **Publications and presentations:**

a) M. Zhou, "*Dynamic Shear Failure Resistance of Structural Metals*", Symposium on the Dyanmic Deformation and Failure Mechanics of Materials, Caltech, Pasadena, CA, May 22-24, 1997.
b) K. Minnaar and M. Zhou, "*Ductile Shear Failure during Deformation Localization*", Symposium on Ductile Damage and Failure Mechanics, McNU'97, June 29- July 2, 1997, Northwestern University, Chicago, IL.
c) K. Minnaar and M. Zhou, "*An Analysis of the Shear Failure Resistance of Structural Metals*", to be submitted to *J. Mech. Phys. Solids*.

18: **Participants in research grant: (PI, co-PI, grad students, undergraduate students, post-docs; specify minority/female participants)**

P.I.:	Min Zhou
Graduate student:	Karel Minnaar
Undergraduate students:	Ken Len
	Akwate Watkins (African American)
	Dawn Amos (female)

19. **Other Grants/contracts: (For each, provide agency, title, period, budget)**

a) Time-Resolved Analysis of the Dynamic Behavior of Granular Materials, AFOSR, 12/1/96-8/30/99, $358,580.

b) ASSERT: Constitutive and Failure Behavior of Granular Materials, AFOSR, 12/1/96-8/30/99, $110,000.

c) Impact Damage and Residual Strength of Structural Composites, ONR/CAU, 7/1/97-6/30/99, $105,000, pending.

20. **Other information:**

A Progress Report for the Project

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Min Zhou
Georgia Institute of Technology

August 1, 1996 - June 30, 1997

Summary:

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Experiments:

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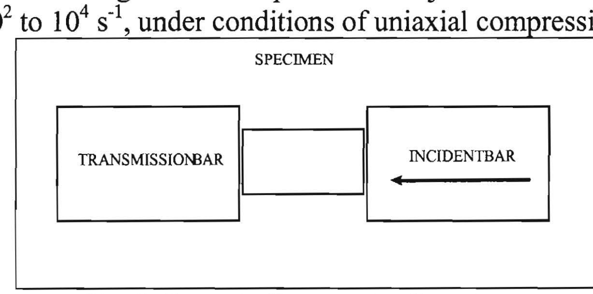

Fig. 1 Dynamic Compression Experiment

2. Dynamic shear failure experiment: This experiment uses a hat-shaped specimen and is conducted on a split Hopkinson compression bar. The compression loading causes intense shear deformation in the ligament of the specimen. The maximum amount of deformation (Δ) permitted is controlled by using stoppers of different thicknesses, therefore allowing the deformation and failure to be "frozen" at different stages of development of microscopic analyses. The configuration of the specimen is shown in Fig. 3.

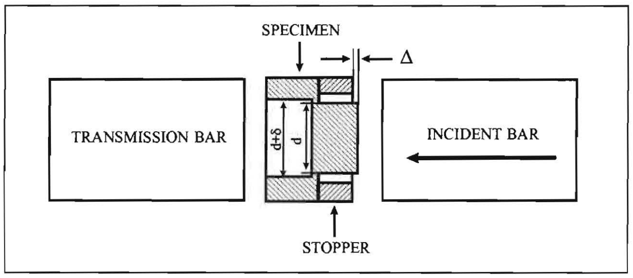

Fig. 2 Dynamic shear failure experiment using a hat specimen

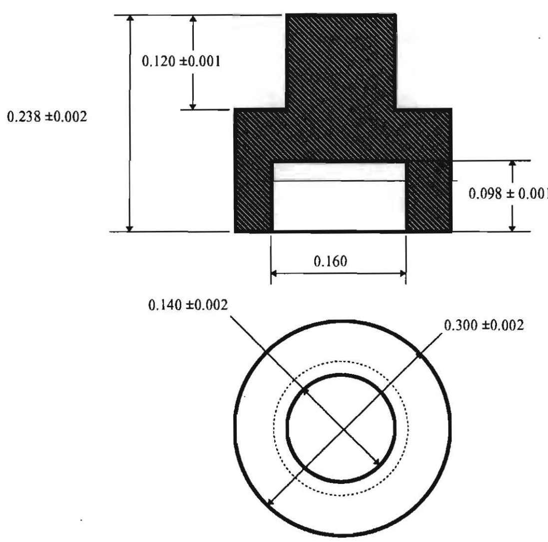

Fig. 3 Hat-shaped Specimen for Shear Failure Analysis

Results:

1. <u>Constitutive response:</u>

The stress-strain response of the materials at a nominal strain rate of 2.5×10^3 s^{-1} are shown in Fig. 4. The curves indicate similar behavior for the steels and much higher flow stresses for Ti-6Al-4V. Also, the precipitous drop in stress for this material indicates for formation of shear bands which are not observed in the steels.

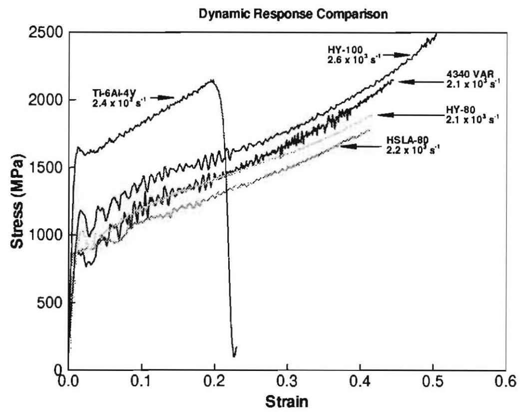

Fig. 4 Constitutive Behavior of the materials Analyzed

2. <u>Shear Failure response:</u>

Shear failure experiments have been conducted on the materials using stopper thickness values between 2-2.9 mm. Shear bands at various stages of development between initiation and eventual rupture have been captured in specimens. The corresponding shear stress-strain curves showing the evolution of the stress carrying capacities of the materials have been recorded. A set of curves for HY-80 are shown in Fig. 5. Comparisons of curves for different materials are shown in Fig. 6 for a stopper thickness of 2.6 mm and Fig. 7 for a stopper thickness of 2.28 mm. The drops in stress signifies the loss of stress carrying capacities and the subsequent increases indicate contact with the stopper rings, therefore, end of shear deformation in the materials. It is clear that Ti-6Al-4V is loses its stress-carrying capacities at a much smaller strain level than the steels. Also, there is a large variation in the shear failure resistance of the steels.

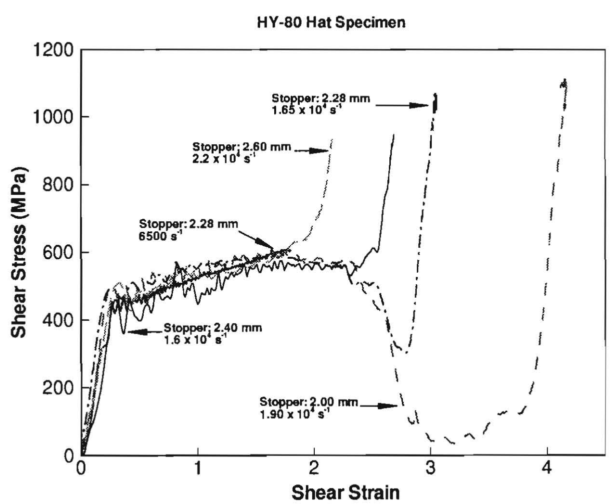

Fig. 5 Shear Stress-strain Curves for HY-80 Steel

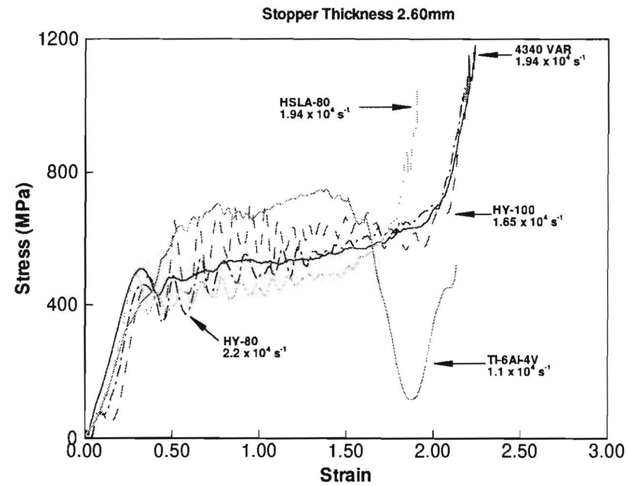

Fig. 6 A comparison of Shear Stress-strain Curves for Different materials (stopper thickness: 2.60 mm)

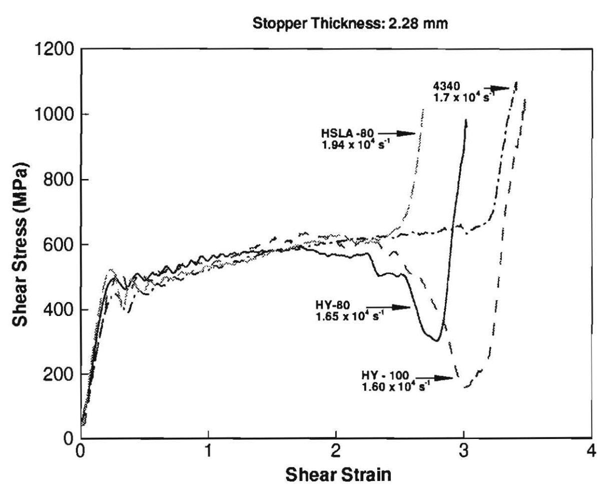

Fig. 7 A comparison of Shear Stress-strain Curves for Different materials (stopper thickness: 2.28 mm)

3. Microscopic characterization

Optical and scanning electron microscopy have been used to analyze the morphology of shear bands and the ductile rupture inside them. It is found that the eventual rupture pays an important role in affecting the progression of shear failure. The microscopic morphology of the shear band and fracture path in a HY-80 specimen is shown in Fig. 8.

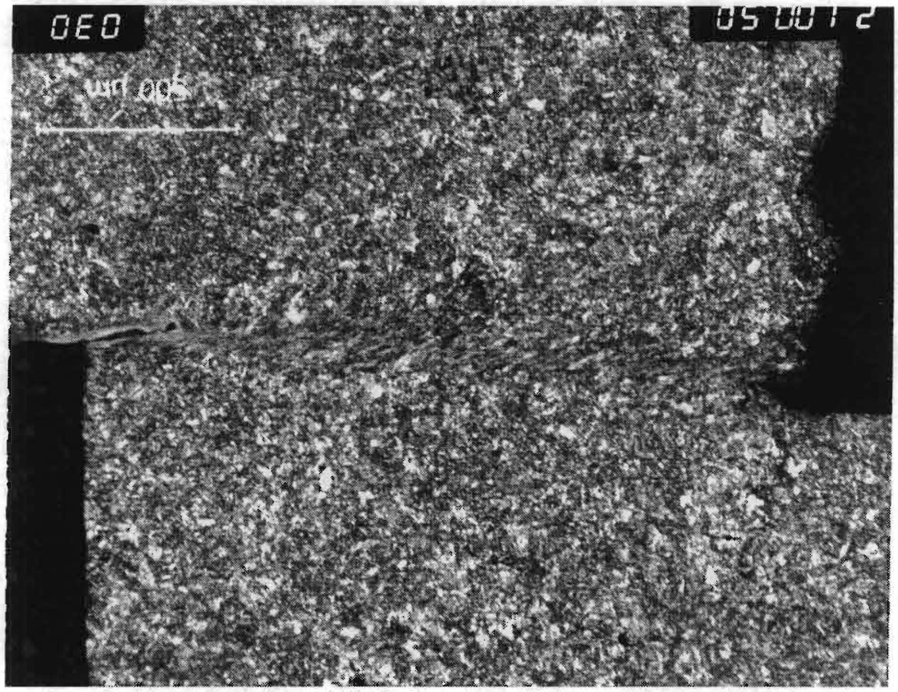

Fig. 8 Shear band in a HY-80 Specimen (stopper thickness: 2.4 mm)

Current Activity:

We are continuing our research in the following areas:

(1) Finite element simulation and modeling of the shear failure process. The modeling is conducted using fully dynamic finite element calculations that account for inertia, finite deformation kinematics, strain rate hardening, thermal softening and heat conduction.

(2) We plan to conduct penetration experiments on the materials to verify our understanding the shear failure resistance.

E-25-L63
N/A

A Progress Report for the Project

DYNAMIC FAILURE BEHAVIOR OF NAVAL STRUCTURAL STEELS

Min Zhou
Georgia Institute of Technology

Summary:

The objective of this research is to evaluate the factors that determine the dynamic shear failure resistance of structural metals such as HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V. So far, our experimental investigation has focused on the response of HY-80 and HY-100 under dynamic uniaxial compression over the strain rate region of 10^2 to 10^4 s^{-1}. The results show that (1) both materials exhibit significant ductility under the conditions tested; (2) these materials do not show susceptibility to failure in the form of shear banding as demonstrated by other materials under similar conditions; and (3) HY-100 has a higher level of flow strength than HY-80. Our current effort continues to focus on (1) the response of HSLA-100, 4340 and Ti-6Al-4V; (2) shear failure resistance characterization of these materials using a hat-shaped specimen; and (3) fully dynamic finite element simulations that account for inertia, finite deformation kinematics, strain rate hardening, thermal softening and heat conduction.

Experiment:

The configuration of the split-Hopkinson bar compression experiment used is shown in Fig. 1. This experiment subjects materials to dynamic loading at strain rates between 10^2 to 10^4 s^{-1}, under conditions of uniaxial compression states of stress. So far, experiments have focused on HY-80 and HY-100. The microstructure of the HY-100 steel before test is shown in Fig. 2.

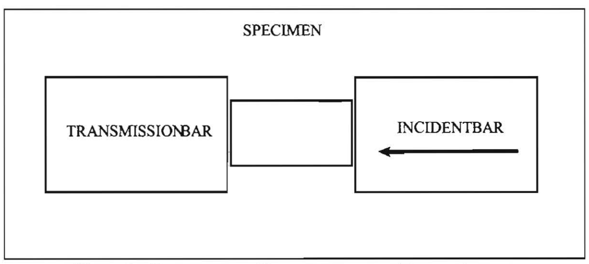

Fig. 1 Dynamic Compression Experiment

Fig. 2 Microstructure of HY-100 Steel

Results:

Experiments conducted so far have been on the compression Hopkinson bar at Georgia Tech. Before formal experiments where conducted, we analyzed the effects of applying a pulse shaper to achieve more uniform strain rate histories in specimens. It was found that the application of a aluminum disk (pulse shaper) causes specimens to be deformed at more uniform strain rate histories. As a result, all experiments reported here included the use of an aluminum pulse shaper.

The stress-strain curves for the two materials studied are shown in Fig. 3 and Fig. 4, respectively. The experiments are conducted to obtain nominal strain rates between 10^2 to 10^4 s^{-1}. The curves demonstrate that (1) the materials show significant strain hardening over the region of strain obtained; (2) the rate of strain hardening is similar for these two materials; (3) the materials do not appear to be strongly rate-sensitive over the range of strain rates shown; (4) the flow stress levels of HY-100 are higher than those of HY-80 at the same strain rate and level of strain.

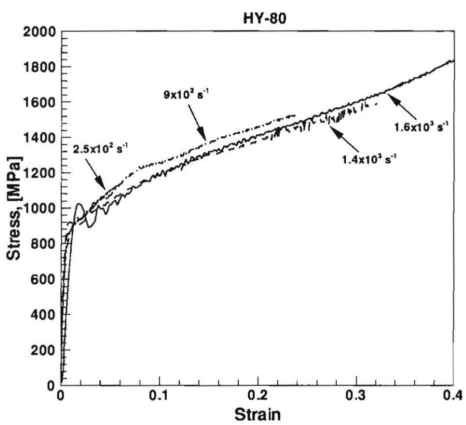

Fig. 3 Constitutive Response of HY-80 Steel

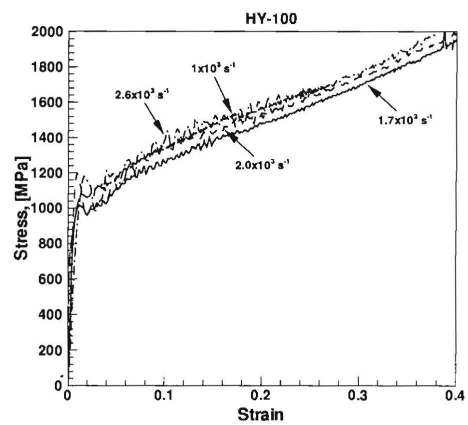

Fig. 4 Constitutive Response opf HY-100 Steel

The results obtained here are in good agreement with results for HY-100 reported by Duffy and coworkers (1992, 1993) obtained using torsional Kolsky bar experiments.

Current Focus:

We are currently conducting our research in the following areas:

(1) Analysis of constitutive response of HSLA-80, HSLA-100, 4340;

(2) Shear failure analysis using a hat-shaped specimen; the configuration of the experiment is shown in Fig. 5. The specimen dimensions are shown in Fig. 6.

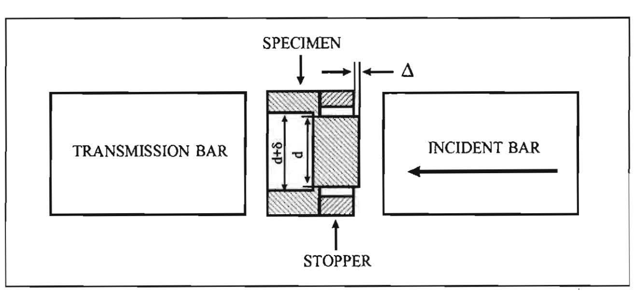

Fig. 5 Configuration of Shear Failure Experiment

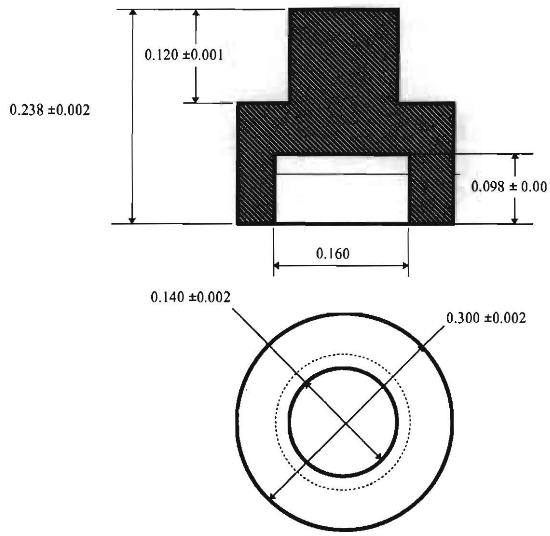

Fig. 6 Hat-shaped Specimen for Shear Failure Analysis

(3) Finite element simulations of the experiments: The numerical simulations account for the effects of inertia, finite deformation kinematics, thermal softening, heat conduction, strain hardening and strain rate hardening. In addition, ductile failure mechanisms will be considered in the analysis. The objective is to evaluate the relative shear failure resistance of the materials.

References:

1. Duffy, J. and Chi, Y.C., (1992), On the Measurement of Local Strain and Temperature During the Formation of Adiabatic Shear Bands, *Mat. Sci. Engng*, **A157**, pp. 195-210.
2. Cho, K. M., Lee, S., Nutt, S. R. and Duffy, J., (1993), Adiabatic Shear Band Formation during Dynamic Torsional Deformation of an HY-100 Steel, *Acta Metall. Mater.*, **41**, pp. 923-932.

E-25-263
N/4

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October 1, 1997

Dr. Albert J. Tucker
Office of Naval Research (ONR334)
Ship Structures and Systems S&T Division
800 North Quincy Street
Arlington, VA 22217-5660

Dear Dr. Tucker,

Enclosed are two copies of my end-of-year report for the project entitled Dynamic Failure Behavior of Naval Structural Steels being carried out at Georgia Tech. I am also sending a copy of the electronic file in Microsoft Word format to cgrabenstein@vrc.com.

Best regards,

Min Zhou
Assistant Professor

Encl.: End of year letter

DYNAMIC FAILURE BEHAVIOR OF NAVAL STRUCTURAL STEELS

Min Zhou
Georgia Institute of Technology
School of Mechanical Engineering
Atlanta, GA 30332-0405

August 1, 1996 - September 30, 1997

Project Objectives

The objective of this research is to evaluate the factors that determine the dynamic shear failure resistance of structural metals including HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V.

Summary of Approach and Recent Accomplishments

Our investigation has focused on

(1) characterizing the response of the constitutive behavior of these materials under dynamic uniaxial compression over the strain rate region of 10^2 to 10^4 s^{-1}, and
(2) assessing the dynamic shear failure resistance of these materials.

The materials are tested in the as-received condition from manufacturers. Their properties meet the military specifications. Our effort focused on the evolution of the load-carrying capacity of these materials during shear band development ***and*** associated microscopic changes. The work so far provided data on the failure behavior of these materials. The data is useful for designers of naval vessels. The findings have been reported in Minnaar and Zhou (1997).

A compression Kolsky bar apparatus is used to achieve well-controlled dynamic shear deformation. This configuration is illustrated in Fig. 1. The specimen is axisymmetric and hat-shaped. Upon impact loading, the specimen is subjected to compression between its two end surfaces. The compression causes shear deformation in the ligament between the solid section and its hollow annulus section. The intense shear in the ligament provides the conditions needed to produce shear band initiation and propagation from the specimen corners. This configuration allows shear band development to different stages to be obtained by choosing the amount of deformation Δ allowed through the use of stoppers with different thickness values. The nominal stress-strain relations are used to evaluate failure progression and load-carrying capacities of different materials.

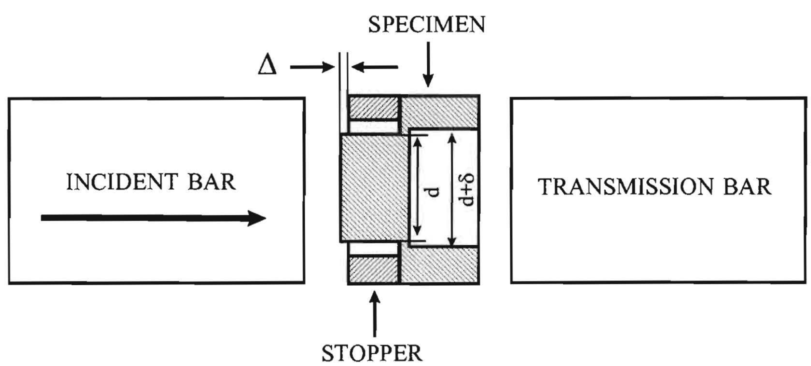

Fig. 1 Dynamic Shear Failure Experiment

Constitutive Response

The dynamic constitutive behaviors of the materials have been analyzed. The stress-strain curves for the five materials over the strain rate range of 10^2-10^4 s^{-1} are shown in Fig. 2(a-e). A comparison of the dynamic responses of the materials for similar strain rates between 2.1-2.4×10^4 s^{-1} is given in Fig. 2(f). The curves show that like their similar quasistatic yield strengths and ultimate tensile strengths, the steels have similar dynamic constitutive behaviors in the strain rate range of 10^2 - 10^4 s^{-1}. The similar quasistatic and dynamic responses indicate that the steels have nearly the same rate-sensitivities in the strain rate range analyzed. It can be seen in Fig. 2(f) that the steels also have nearly the same rate of strain hardening. The similar constitutive behavior is in contrast to their significantly different shear failure behavior observed. This difference highlights the influence of microscopic damage and will be further discussed later in this report.

Ti-6Al-4V has a much stronger rate-sensitivity than those of the steels. In addition, its rate of strain hardening is slightly higher. Despite these factors, this material is more susceptible to shear banding and ductile rupture than the steels, as suggested by the precipitous drops in stress at strains of approximately 0.2. Postmortem analysis revealed that the shear bands occurred along plane approximately 45° from the loading axis. This is inconsistent with the understanding that strong rate-sensitivity and higher strain hardening enhance resistance to shear localization, indicating factors other than rate-sensitivity play a more dominant role in determining shear failure under the conditions analyzed. The high rates of rate sensitivity and strain hardening are in contrast to its high susceptibility to shear failure. This observation further reinforces our conclusion that thermomechanical constitutive response along does not fully determine the dynamic shear failure of structural metals. Instead, microscopic damage accompanying localized deformation plays a significant role and must be considered.

Evolution of Stress-carrying Capacity Throughout Deformation and Failure

The nominal shear stress-strain curves obtained from shear failure experiments for five materials are shown in Fig. 3(a-e). The stress and strain are average values in the specimen ligament. The precipitous drops in shear stress signifies the loss of stress-carrying capacity associated with shear failure development. The increase in stress following the drop on each curve results from the contact of the incident bar and the stopper. It signifies the cessation of deformation in the specimen. To facilitate comparison, the curves for all five materials for a stopper thickness of 2.0 mm ($\gamma_{max} = 4.3$) are shown in Fig. 3(f). Clearly, all materials show a total loss of stress-carrying capacity indicated by the drop of stress to near zero levels. The shape of the curves indicate that the strains at which materials lose all of their stress-carrying capacities increase in the order Ti-6Al-4V → HY-80 → HY-100 → HSLA-80 → 4340. The critical strain level for Ti-6Al-4V is approximately 1.6. Significantly lower than those of the steels. Ti-6Al-4V does not display a period of gradual decrease of stress. Instead, a rapid loss of stress is observed immediately after the onset of localization. The steels, on the other hand, show gradual softening preceding the rapid losses of load-carrying capacity, indicating higher resistance to shear failure.

Microscopic Observations

The deformed microstructures of the steels at nominal shear strain levels of 1.85 and 2.68 are shown in Fig. 4. This series of pictures illustrates the progression of localization and rupture in each material. Consistent with the stress-strain profiles, the micrographs indicate significantly different levels of resistance to shear banding and rupture. The martensitic microstructure of HY-100 makes it more susceptible to the development of intensely localized shear bands. However, its earlier development of localization does not necessarily result in early loss of stress as seen in Fig. 3. Instead, significant loss of strength follows more closely the subsequent ductile rupture of materials.

To quantify the extent of shear localization and rupture, the lengths of shear bands and cracks following the shear bands are compared, see Fig. 5. These two lengths increase with the nominal shear strain inside the ligament. For each of the steels, there is an appreciable difference in the shear band length and the crack length, suggesting development of rupture after localization of strain. For Ti-6Al-4V, the shear band length and the rupture length are very close to each other. This lack of difference for the titanium alloy indicates the near simultaneous occurrence of localization and rupture. Partly because of this rapid development of rupture, Ti-6Al-4V exhibits a much higher degree of susceptibility to the loss of stress-carrying capacity than those of the steels.

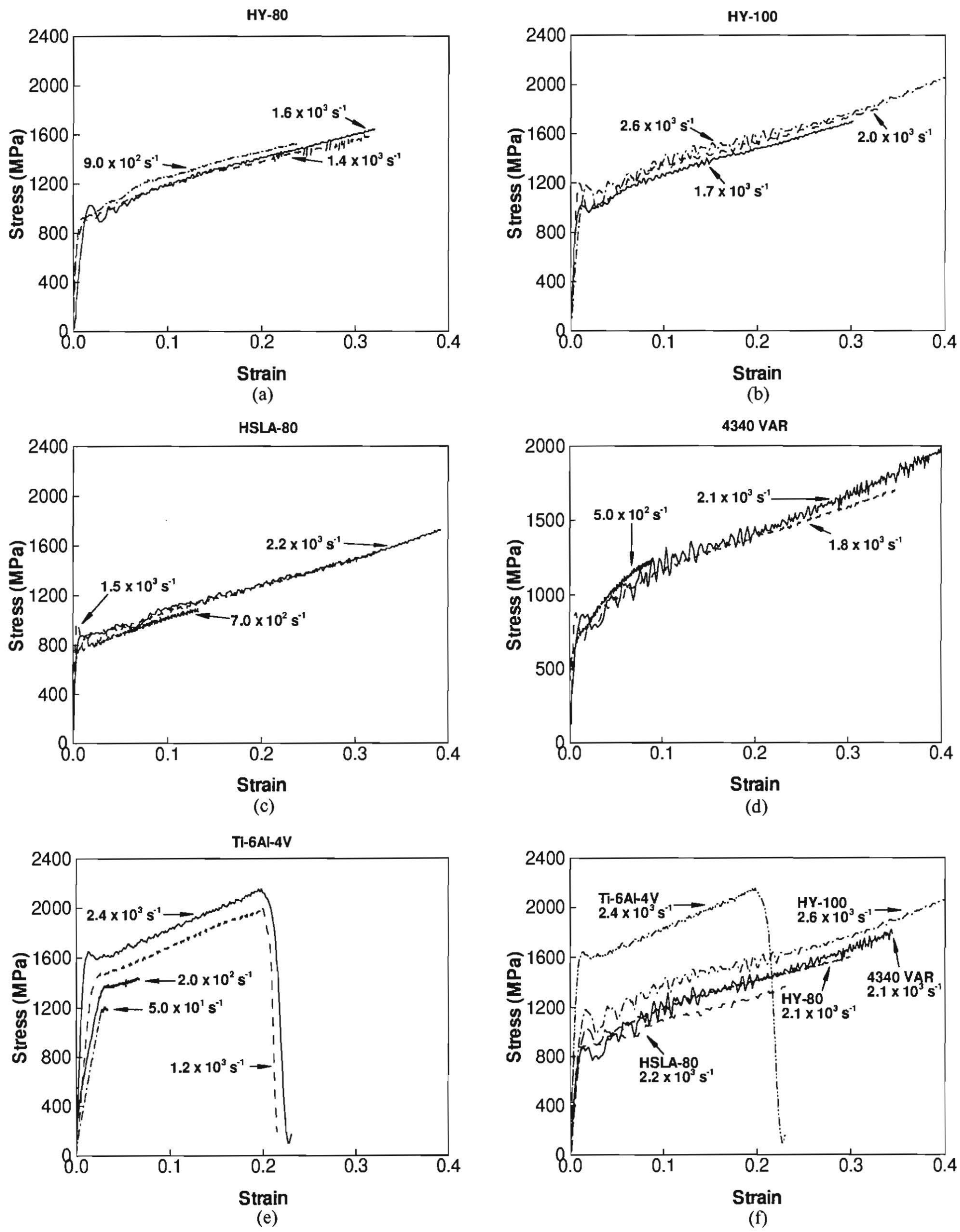

Fig. 2 Dynamic Constitutive Response of Five Structural Metals

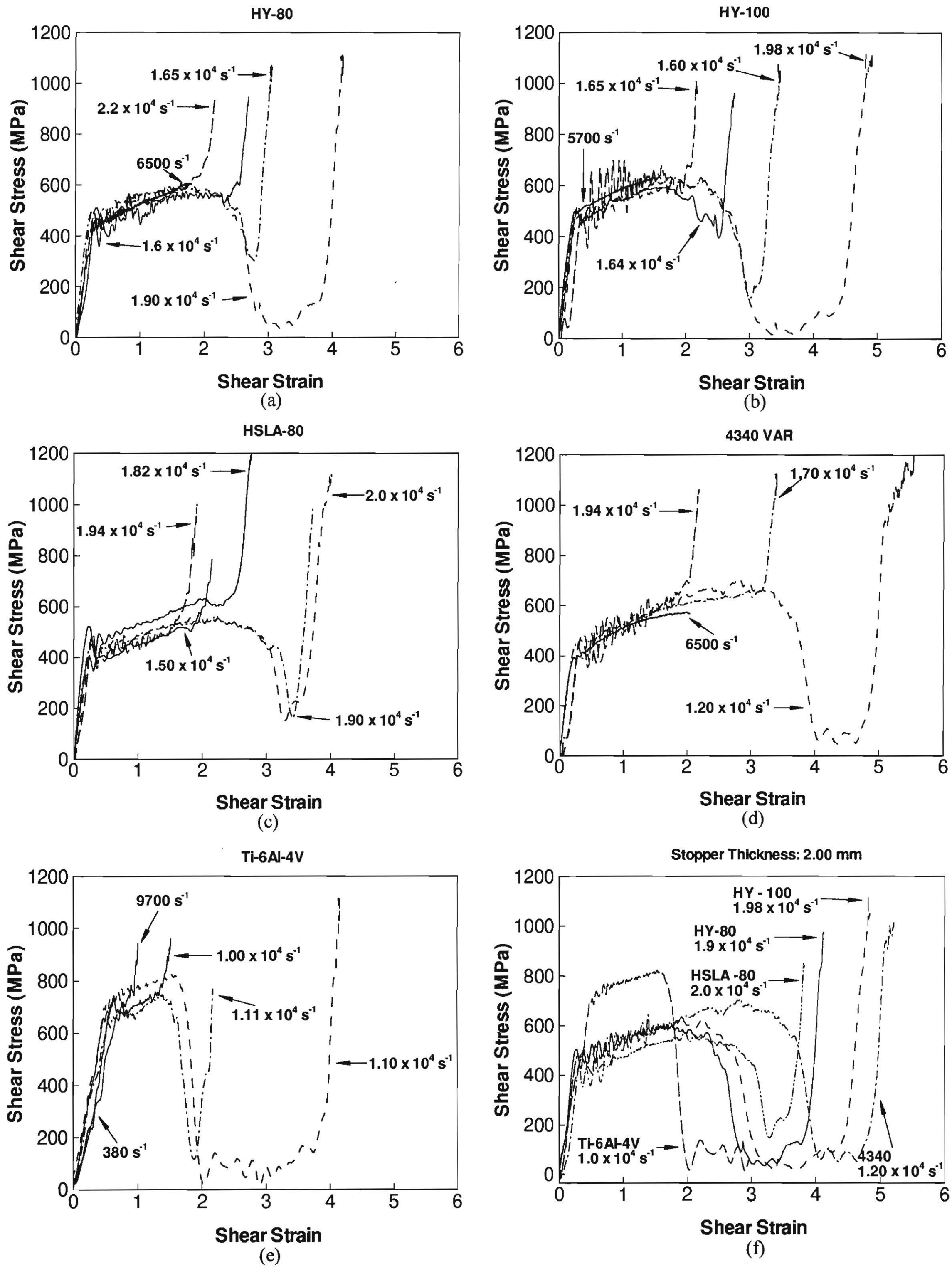

Fig. 3 Evolution of Stress-Carrying Capacity for Five Materials during Dynamic Shear Failure

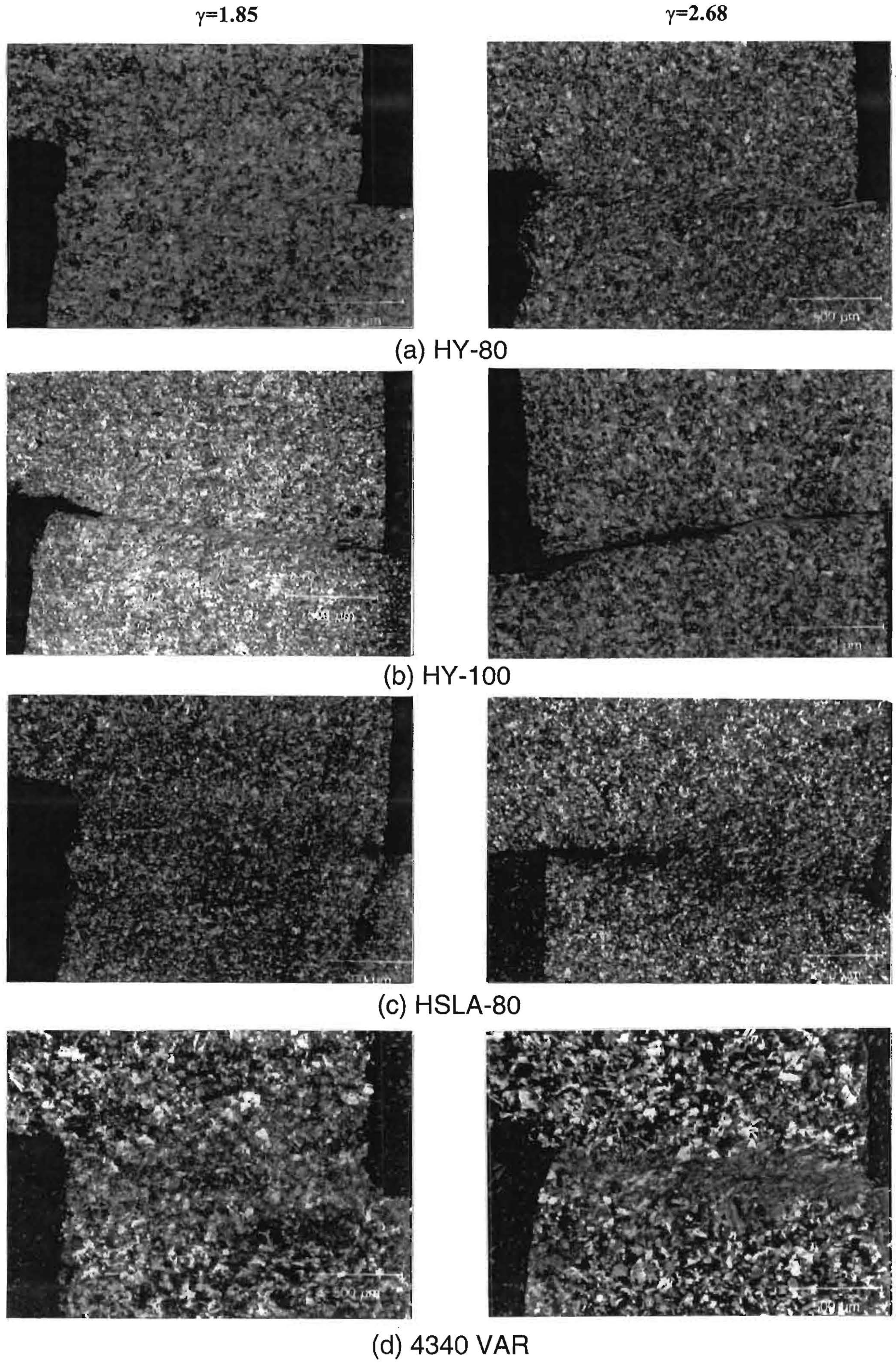

Fig. 7 Morphologies of Strain Localization and Ductile Rupture at γ=1.85 and 2.68 for (a) HY-80,(b) HY-100, (c) HSLA-80, and (d) 4340VAR steels

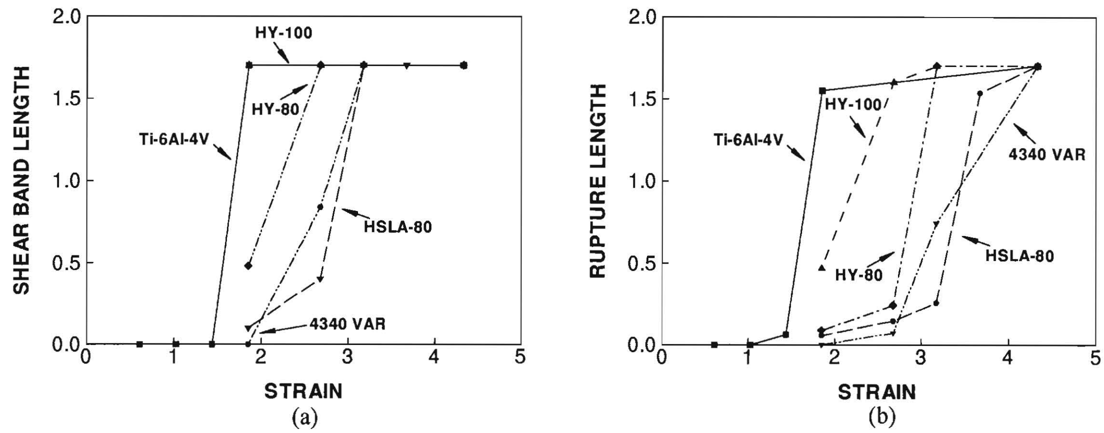

Fig. 5 Shear Band and Rupture Lengths as Functions of Shear Deformation
(a) Shear Band Length, (b) Rupture Length

The findings of this research are:

1) Despite their significantly different static properties such as yield strength and hardness, chemical compositions and heat treatment, the steels (HY-80, HY-100, HSLA-80, HSLA-100, and 4340) have very similar dynamic constitutive behaviors in the strain rate range of 10^2 - 10^4 s^{-1}.
2) There is a relatively large variation in the shear failure resistance among the steels, as measured by the stress strain curves and the critical shear strain for failure. This is in contrast to their similar thermomechanical constitute behaviors observed;
3) While the steels are also relatively rate-insensitive, the titanium alloy (Ti-6Al-4V) shows much stronger rate-sensitivity in the same strain rate regime. However, despite this higher rate-sensitivity, Ti-6Al-4V is more susceptible to shear banding and rupture than the steels. This finding is in contrast to the fact that strain rate dependence enhances resistance to shear localization;
4) Based on an approximate shear localization model of Grady (1994) which accounts for the strain sensitivity, thermal softening and heat conduction, very similar band dissipation energy (G_s) and shear band toughness (K_s) values are predicted for the steels, see Table 1. The toughness does not include the influence of microscopic damage and rupture inside shear bands on the stress-carrying capacity of materials. The significantly different shear failure behaviors of the steels observed demonstrate that rupture inside shear bands is an important part of the failure process that should to be considered in evaluating failure.

Table 1 Dissipation energy and shear band toughness

Material	Flow Stress (MPa)	Dissipation Energy Γ_s (KJ/m^2)	Shear Band Toughness K_s ($MPa\sqrt{m}$)
HY-80	1460	125.2	142.221
HY-100	1530	120.9	139.745
HSLA-80	1280	138.2	149.414
4340VAR	1450	125.9	142.588
Ti-6Al-4V	2000	3.935	18.861

Current Activities:

(1) Finite element simulation and modeling of the shear failure process. The modeling is conducted using fully dynamic finite element calculations that account for inertia, finite deformation kinematics, strain rate hardening, thermal softening and heat conduction.
(2) We plan to conduct penetration experiments on the materials to verify our understanding the shear failure resistance.

Relevance to the Navy:

This research is relevant to the design of naval structures in maximizing the structural integrity for various service conditions. This contribution can be reflected in four ways: (1) the shear failure resistance comparison and shear failure toughness measure developed will provide guidance for the selection of appropriate materials; (2) understanding of how shear failure propagates in materials will enable optimization of structural design to minimize damage; and (3) understanding gained will provide suggestion for the revision and improvement of naval structural metals and contribute to the development of more failure-resistant materials.

Recent publications:

1. M. Zhou, A. J. Rosakis and G. Ravichandran, Dynamically Propagating Shear Bands in Impact-loaded Prenotched plates, I - Experimental Investigations of Temperature Signatures and Propagation Speed, _J. Mech. Phys. Solids_, **44**, pp.981-1006, 1996.
2. M. Zhou, G. Ravichandran and A. J. Rosakis, Dynamically Propagating Shear Bands in Impact-loading Prenotched plates, II - Numerical Simulations, _J. Mech. Phys. Solids_, **44**, pp.1007-1032, 1996.
3. M. Zhou and R. J. Clifton, "Dynamic Ductile Rupture under the Conditions of Plan Strain, _Int. J. Impact Engng._, **19**, pp.189-206, 1997.
4. M. Zhou, Effects of Microstructure on the Resistance to Shear Localization for a Class of Metal Matrix Composites, _Fatigue Fract. Engng. Mater. Struct._, in press and to appear, 1997.
5. M. Zhou, A. J. Rosakis and G. Ravichandran, On the Growth of Shear Bands and Failure-Mode Transition in Prenotched Plates: A comparison of singly and doubly notched specimens, _Int. J. Plasticity_, in press and to appear, 1997.
6. M. Zhou and R. J. Clifton, Dynamic Constitutive and Failure Behavior of a Two-phase Tungsten Composite, _J. App. Mech._, in press and to appear, 1997.
7. M. Zhou, The Growth of Shear Bands in Composite Microstructures, _Int. J. Plasticity_, in press and to appear, 1997.
8. K. Minnaar and M. Zhou, An Analysis of the Dynamic Shear Failure Resistance of Structural Metals, _J. Mech. Phys. Solids_, in press and to appear, 1997.
9. K. Minnaar and M. Zhou, Microstructural Failure Mechanisms during dynamic Shear Deformation of Structural Metals, manuscript in preparation and to be submitted to _Int. J. Plasticity_, 1997.
10. A. J. Rosakis, G. Ravichandran and M. Zhou, Real-time Experimental Observations of Two-dimensional Dynamic Shear Band Growth, AMD-Vol.**200**/MD-Vol.**57**, pp. 95-100, Plasticity and Fracture Instabilities in Materials, 1995.
11. A. J. Rosakis, G. Ravichandran and M. Zhou, Dynamically Growing Shear Bands in Metals: A study of Transient Temperature and Deformation Fields, *Proc. IUTAM Symposium on Nonlinear Analysis of Fracture*, September 1995.

FY97 End of Fiscal Year Letter
(Oct. 01 1996 - Sept. 30 1997)

ONR GRANT INFORMATION

1. Grant Title:	Dynamic Failure Behavior of Naval Structural Steels
2. Performing Organization:	Georgia Tech Research Corporation/ Georgia Institute of Tech
3. PI Name:	Min Zhou
Address:	School of Mechanical Engineering Georgia Institute of Technology Atlanta, GA 30332-0405
Telephone No.:	(404) 894-3294
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4. Grant No.:	N00014-96-1-1195
5. R&T No.:	96PR07524-00
6. Duration of Current Grant:	August 1, 1996 to July 31, 1998
Start Date:	August 1, 1996
End Date:	July 31, 1998
7. ONR Scientific Officer:	Dr. Yapa D. S. Rajapakse

List of Publications/Reports/Presentations

1. **Papers published in Referred Journals:**

1. M. Zhou, A. J. Rosakis and G. Ravichandran, Dynamically Propagating Shear Bands in Impact-loaded Prenotched plates, I - Experimental Investigations of Temperature Signatures and Propagation Speed, J. Mech. Phys. Solids, **44**, pp.981-1006, 1996.
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10. A. J. Rosakis, G. Ravichandran and M. Zhou, Real-time Experimental Observations of Two-dimensional Dynamic Shear Band Growth, AMD-Vol.200/MD-Vol.57, pp. 95-100, Plasticity and Fracture Instabilities in Materials, 1995.
11. A. J. Rosakis, G. Ravichandran and M. Zhou, Dynamically Growing Shear Bands in Metals: A study of Transient Temperature and Deformation Fields, *Proc. IUTAM Symposium on Nonlinear Analysis of Fracture*, September 1995.

3. Presentations

a. Invited:

1) M. Zhou, "*Dynamic Shear Failure Resistance of Structural Metals*", Symposium on the Dynamic Deformation and Failure Mechanics of Materials, Caltech, Pasadena, CA, May 22-24, 1997.

b. Contributed:

1) K. Minnaar and M. Zhou, "*Ductile Shear Failure during Deformation Localization*", Symposium on Ductile Damage and Failure Mechanics, McNU'97, June 29- July 2, 1997, Northwestern University, Chicago, IL.
2) *M. Zhou, The growth of shear bands in composite microstructures*, ASME Winter Annual Meeting, Atlanta, GA, Nov., 1996;
3) *M. Zhou, Numerical Analyses of the Influence of Microstructural Changes on Shear Localization in Tungsten Composites*, 14th Army Symposium on Solid Mechanics, Myrtle Beach, SC, October, 1996.
4) *M. Zhou, Effect of microstructure on propagation of shear bands*, ASME Summer Annual Meeting, Baltimore, MD, June 1996;

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Final Report Information
(Aug. 1, 1996 – Sept. 30, 1998)

ONR GRANT INFORMATION

1. Grant Title:	Dynamic Failure Behavior of Naval Structural Steels
2. Performing Organization:	Georgia Tech Research Corporation/ Georgia Institute of Technology
3. PI Name:	Min Zhou
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E-mail Address:	min.zhou@me.gatech.edu
4. Grant No.:	N00014-96-1-1195
5. R&T No.:	96PR07524-00
6. Duration of Current Grant:	August 1, 1996 to September 30, 1998
Start Date:	August 1, 1996
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7. ONR Scientific Officer:	Dr. Yapa D. S. Rajapakse

List of Publications/Reports/Presentations

1. **Papers published in and submitted to referred journals:**

1. M. Zhou, A. J. Rosakis and G. Ravichandran, Dynamically Propagating Shear Bands in Impact-loaded Prenotched plates, I - Experimental Investigations of Temperature Signatures and Propagation Speed, *J. Mech. Phys. Solids*, **44**, pp.981-1006, 1996.
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4. M. Zhou, Effects of Microstructure on the Resistance to Shear Localization for a Class of Metal Matrix Composites, *Fatigue and Fracture of Engineering Materials Structures*, **21**, pp. 425-438, 1998.
5. M. Zhou, A. J. Rosakis and G. Ravichandran, On the Growth of Shear Bands and Failure-Mode Transition in Prenotched Plates: A comparison of singly and doubly notched specimens, *Int. J. Plasticity*, **14**, pp.435-451, 1998.
6. M. Zhou and R. J. Clifton, Dynamic Constitutive and Failure Behavior of a Two-phase Tungsten Composite, *Journal of Applied Mechanics*, **64**, pp. 487-494, 1997.
7. M. Zhou, The Growth of Shear Bands in Composite Microstructures, *Int. J. Plasticity*, **14**, pp. 733-754, 1998.
8. K. Minnaar and M. Zhou, An Analysis of the Dynamic Shear Failure Resistance of Structural Metals, *J. Mech. Phys. Solids*, **46**, 1998.
9. S.W. Park, M. Zhou and D. R. Veazie, "Time-resolved Impact Response and Damage of Fiber-reinforced Composite Laminates", submitted to *Journal of Composite Materials*, 1998.
10. S. W. Park and M. Zhou, "Separation of Elastic Waves in Split Hopkinson Bars using One-point Strain Measurements", submitted to *Experimental Mechanics*, 1998.

2. **Conference papers, thesis, and papers to be submitted:**

11. K. Minnaar, Comparison and Analyses of the Dynamic Shear Failure Resistance of Structural Metals, M.S. Thesis, Georgia Institute of Technology, Nov. 1997;
12. K. Minnaar and M. Zhou, Microstructural Failure Mechanisms during Dynamic Shear Deformation of Structural Metals, manuscript in preparation and to be submitted to *Int. J. Plasticity*, 1998.
13. S. W. Park and M. Zhou, (1998), "Ultrasonic Characterization of Impact-Induced Damage in Fiber-reinforced Laminated Composites", Fifth International Conference on Composites Engineering (ICCE/5), pp. 711-712, July 5-11, Las Vegas, NV.
14. S. W. Park and M. Zhou, (1998), "An Improved Analysis Technique for Impact Experiments on Composites using the Split Hopkinson Pressure Bar", Fifth International Conference on Composites Engineering (ICCE/5), pp. 1021-1022, July 5-11, Las Vegas, NV.
15. M. Zhou, A. J. Rosakis and G. Ravichandran, "Adiabatic Shear Band Formation in Asymmetrically Impacted Prenotched Plates - An Investigation of Temperature Signatures", *Materials Instabilities: Theory and Application*, AMD-Vol. **183**/MD-Vol. **50**, pp. 35-49, Nov., 1994.
16. M. Zhou, R. J. Clifton and A. Needleman, "Shear Bands in Pressure-shear Plate Impact", *Proc. 13th Army Symposium on Solid Mechanics*, pp. 117-135, Aug. 1993, Plymouth, MA.

17. A. J. Rosakis, G. Ravichandran and M. Zhou, "Real-Time Experimental Observations of Two-dimensional Dynamic Shear Band Growth", AMD-Vol. **200**/MD-Vol. **57**, pp. 95-100, Plastic and Fracture Instabilities in Materials, 1995.
18. A. J. Rosakis, G. Ravichandran and M. Zhou, "Dynamically Growing Shear Bands in Metals: A study of Transient Temperature and Deformation Fields", *Proc. IUTAM Symposium on Nonlinear Analysis of Fracture*, September 1995, Cambridge, England.

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b. Contributed:

1) S. W. Par and M. Zhou, Impact response, Damage and Residual Strength of Fiber-reinforced laminate Composites, Fifth International Conference on Composites Engineering (ICCE/5), July 5-11, Las Vegas, NV, with S. W. Park.
2) M. Zhou, *Dynamic Failure Resistance of Structural Materials*, Office of Naval Research 6.1/6.2 Workshop at Naval Surface Warfare Center-Carderock, MD, May 5-7, 1998
3) J. Zhai and M. Zhou, *Numerical Simulations of Dynamic Failure in Structural Composites*, 13^{th} US National congress of Applied Mechanics, Gainesville, FL, June 21-26, 1998.
4) K. Minnaar and M. Zhou, *Ductile Shear Failure during Deformation Localization*, Symposium on Ductile Damage and Failure Mechanics, McNU'97, June 29- July 2, 1997, Northwestern University, Chicago, IL.
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7) M. Zhou, *Effect of microstructure on propagation of shear bands*, ASME Summer Annual Meeting, Baltimore, MD, June 1996;

List of Honors/Awards

Name of Person Receiving award	Recipients institution	Name, sponsor and purpose of award
Min Zhou	Georgia Institute Technology	IMM fellowship for 1997 IMM/NSF Young Investigator Symposium

Summary
Publications/Patents/Presentations/Honors/ Participants
(Number Only)

		ONR Supported	Non ONR
a.	Number of Papers Submitted to Refereed Journals but not yet published:	3	3
b.	Number of Papers Published in Refereed Journals:	8	2
c.	Number of Books or Chapters Submitted but not yet Published:	1	0
d.	Number of Books or Chapters Published:		
e.	Number of Printed Technical Reports & Non-Refereed Papers:	3	4
f.	Number of Patents Filed:		
g.	Number of Patents Granted:		
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings:	1	0
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings:	7	4
j.	Honor/Awards/Prizes for Contract/Grant Employees:	1	
k.	Number of Graduate Students and Post-Docs Supported at least 25% this year on contract grants:	2	4
	Grad Students: TOTAL	1	
	Female		
	Minority		
	Post Doc: TOTAL	1	1
	Female		
l.	Number of Female or Minority PIs or Co-PIs		
	New Female		
	Continuing Female		
	New Minority		
	Continuing Minority	1	

Final Report for ONR Project Entitled

DYNAMIC FAILURE BEHAVIOR OF NAVAL STRUCTURAL STEELS

Min Zhou
Georgia Institute of Technology
School of Mechanical Engineering
Atlanta, GA 30332-0405

August 1, 1996 – September 30, 1998

Project Objective

The objective of this two-year research is to

(1) Characterize the dynamic constitutive behavior of structural metals including HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V;
(2) evaluate the factors that determine their dynamic shear failure resistance; and
(3) obtain experimental quantification of the failure resistance of these materials.

Summary of Approach and Accomplishments

A combined experimental and numerical approach has been employed in the investigation. The work carried out consists of experimental characterization of failure behavior and numerical simulations. Specific accomplishments are:

(1) The responses of the above materials over a wide range of strain rate (of 10^{-3} to 10^{4} s^{-1}) have been characterized;
(2) The dynamic shear failure resistances of these materials have been experimentally characterized;
(3) A novel Cohesive Finite Element Method (CFEM) has been developed for the modeling of dynamic shear failure, accounting for microscopic rupture as well as thermomechanical response. Numerical simulations have been carried to illustrate the failure behavior and failure mechanisms. This accomplishment exceeded the initial scope of tasks.

The materials are tested in the as-received condition from manufacturers. Their properties meet the military specifications. Our effort focused on the evolution of the load-carrying capacity of these materials during shear band development *and* associated microscopic changes. The work so far provided data on the failure behavior of these materials. The data is useful for designers of naval vessels. The findings have been reported in Minnaar and Zhou (1998).

A compression Kolsky bar apparatus is used to achieve well-controlled dynamic shear deformation. This configuration is illustrated in Fig. 1. The specimen is axisymmetric and hat-shaped. Upon impact loading, the specimen is subjected to compression between its two end surfaces. The compression causes shear deformation in the ligament between the solid section and its hollow annulus section. The intense shear in the ligament provides the conditions needed to produce shear band initiation and propagation from the specimen corners. This configuration allows shear band development to different stages to be obtained by choosing the amount of deformation Δ allowed through the use of stoppers with different thickness values. The nominal stress-strain relations are used to evaluate failure progression and load-carrying capacities of different materials.

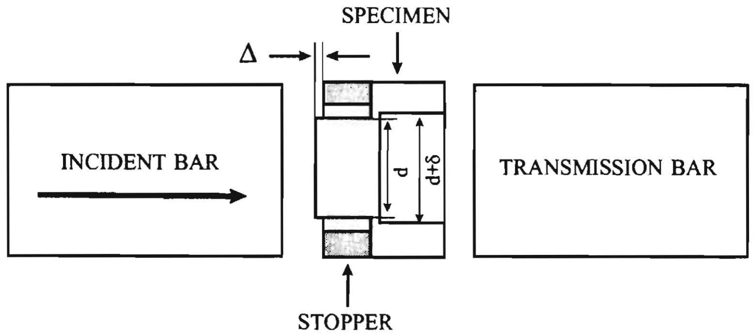

Fig. 1 Dynamic Shear Failure Experiment

Constitutive Response and Failure Parameters

The constitutive behaviors of the materials over a wide range of loading have been analyzed using dynamic compression and quasistatic tension. The combination of dynamic and quasistatic experiments are chosen to yield a complete set of experimental characterization required for cohesive finite element simulations. The stress-strain curves for the five materials over the strain rate range of 10^{-3}-10^{4} s^{-1} are shown in Fig. 2(a-e). A comparison of the dynamic responses of the materials for similar strain rates between 2.1-2.4×10^{4} s^{-1} is given in Fig. 2(f). The curves show that like their similar quasistatic yield strengths and ultimate tensile strengths, the steels have similar dynamic constitutive behaviors in the strain rate range of 10^{2} - 10^{4} s^{-1}. The similar quasistatic and dynamic responses indicate that the steels have nearly the same rate-sensitivities in the strain rate range analyzed. It can be seen in Fig. 2(f) that the steels also have nearly the same rate of strain hardening. The similar constitutive behavior is in contrast to their significantly different shear failure behavior observed. This difference highlights the influence of microscopic damage and will be further discussed later in this report.

Ti-6Al-4V has a much stronger rate-sensitivity than those of the steels. In addition, its rate of strain hardening is slightly higher. Despite these factors, this material is more susceptible to shear banding and ductile rupture than the steels, as suggested by the precipitous drops in stress at strains of approximately 0.2. Postmortem analysis revealed that the shear bands occurred along plane approximately 45° from the loading axis. This is inconsistent with the understanding that strong rate-sensitivity and higher strain hardening enhance resistance to shear localization, indicating factors other than rate-sensitivity play a more dominant role in determining shear failure under the conditions analyzed. The high rates of rate sensitivity and strain hardening are in contrast to its high susceptibility to shear failure. This observation further reinforces our conclusion that thermomechanical constitutive response along does not fully determine the dynamic shear failure of structural metals. Instead, microscopic damage accompanying localized deformation plays a significant role and must be considered. The rate-dependence of the material behaviors is characterized in Fig. 3.

Evolution of Stress-carrying Capacity Throughout Deformation and Failure

The nominal shear stress-strain curves obtained from shear failure experiments for five materials are shown in Fig. 4(a-e). The stress and strain are average values in the specimen ligament. The precipitous drops in shear stress signifies the loss of stress-carrying capacity associated with shear failure development. The increase in stress following the drop on each curve results from the contact of the incident bar and the stopper. It signifies the cessation of deformation in the specimen. To facilitate comparison, the curves for all five materials for a stopper thickness of 2.0 mm (γ_{max} = 4.3) are shown in

Fig. 4(f). Clearly, all materials show a total loss of stress-carrying capacity indicated by the drop of stress to near zero levels. The shape of the curves indicate that the strains at which materials lose all of their stress-carrying capacities increase in the order Ti-6Al-4V → HY-80 → HY-100 → HSLA-80 → 4340. The critical strain level for Ti-6Al-4V is approximately 1.6. Significantly lower than those of the steels. Ti-6Al-4V does not display a period of gradual decrease of stress. Instead, a rapid loss of stress is observed immediately after the onset of localization. The steels, on the other hand, show gradual softening preceding the rapid losses of load-carrying capacity, indicating higher resistance to shear failure.

Microscopic Observations

The deformed microstructures of the steels at different nominal shear strain levels have been analyzed to determine the failure parameters in the cohesive finite element models. Consistent with the stress-strain profiles, micrographs indicate significantly different levels of resistance to shear banding and rupture. The martensitic microstructure of HY-100 makes it more susceptible to the development of intensely localized shear bands. However, its earlier development of localization does not necessarily result in early loss of stress as seen in Fig. 4. Instead, significant loss of strength follows more closely the subsequent ductile rupture of materials.

The deformed microstructures of the steels at nominal shear strain levels of 2.0 and 2.5 are shown in Fig. 5. This series of pictures illustrates the progression of localization and rupture in each material. Consistent with the stress-strain profiles, the micrographs indicate significantly different levels of resistance to shear banding and rupture. The martensitic microstructure of HY-100 makes it more susceptible to the development of intensely localized shear bands. However, its earlier development of localization does not necessarily result in early loss of stress as seen in Fig. 4. Instead, significant loss of strength follows more closely the subsequent ductile rupture of materials.

To quantify the extent of shear localization and rupture, the lengths of shear bands and cracks following the shear bands are compared, see Fig. 6. These two lengths increase with the nominal shear strain inside the ligament. For each of the steels, there is an appreciable difference in the shear band length and the crack length, suggesting development of rupture after localization of strain. For Ti-6Al-4V, the shear band length and the rupture length are very close to each other. This lack of difference for the titanium alloy indicates the near simultaneous occurrence of localization and rupture. Partly because of this rapid development of rupture, Ti-6Al-4V exhibits a much higher degree of susceptibility to the loss of stress-carrying capacity than those of the steels.

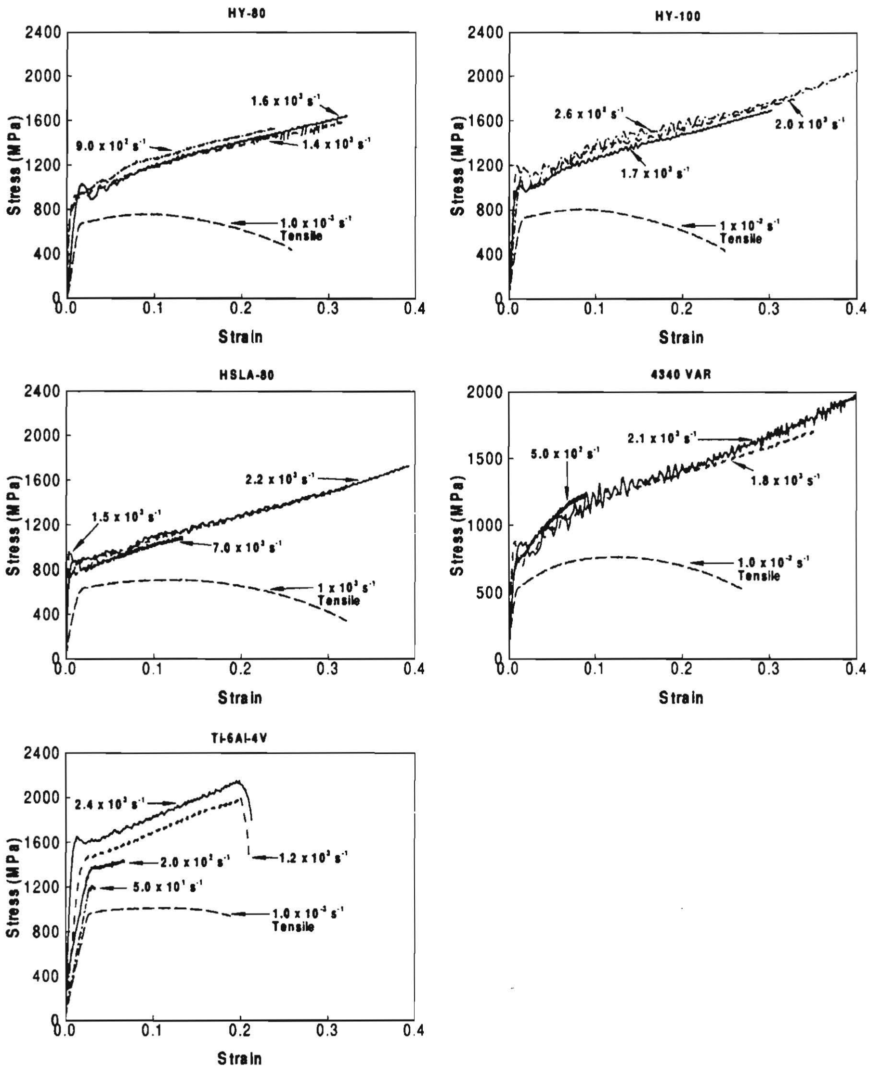

Fig. 2 Dynamic Constitutive Response of Five Structural Metals

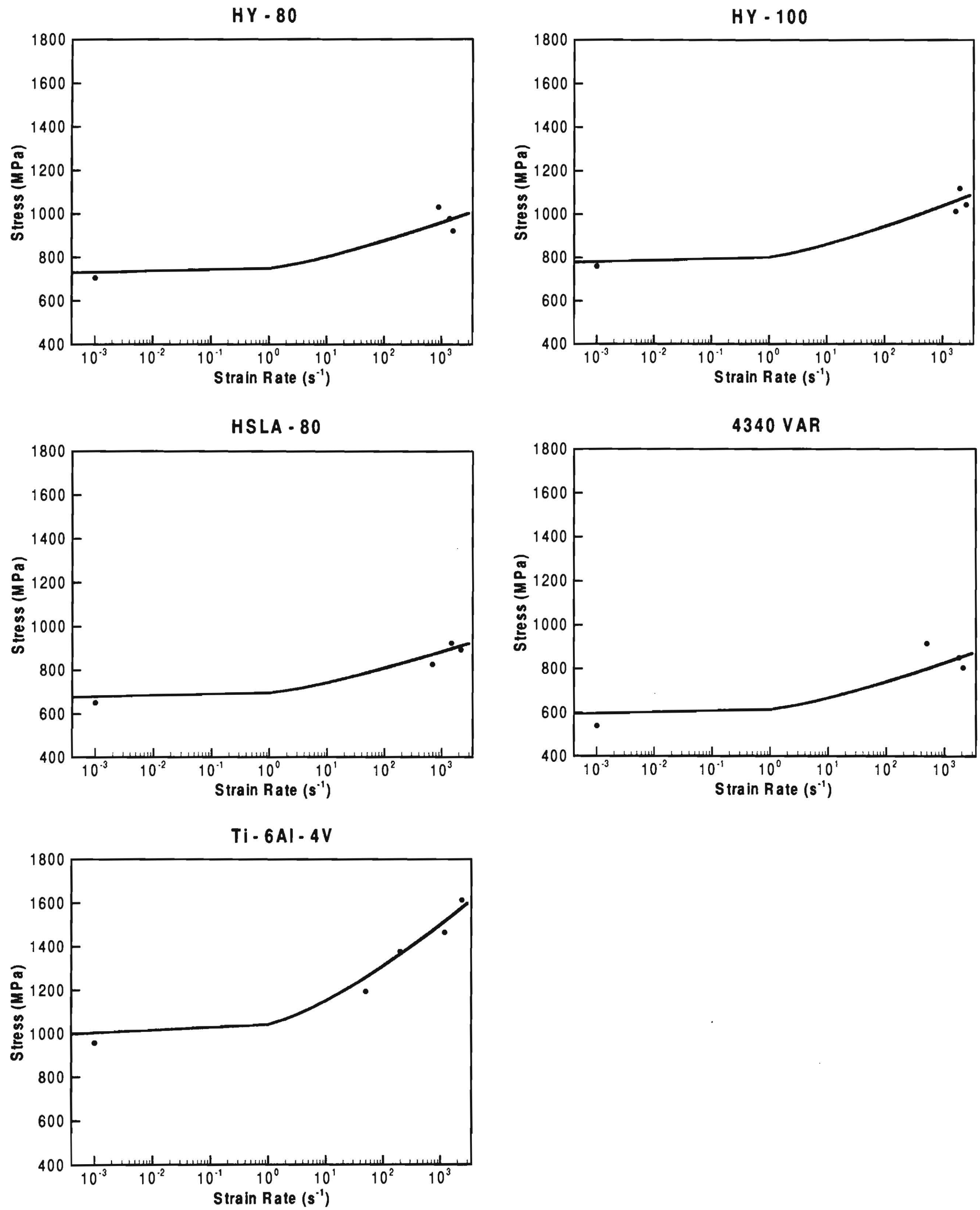

Fig. 3 Characterization of the rate-dependence of the materials

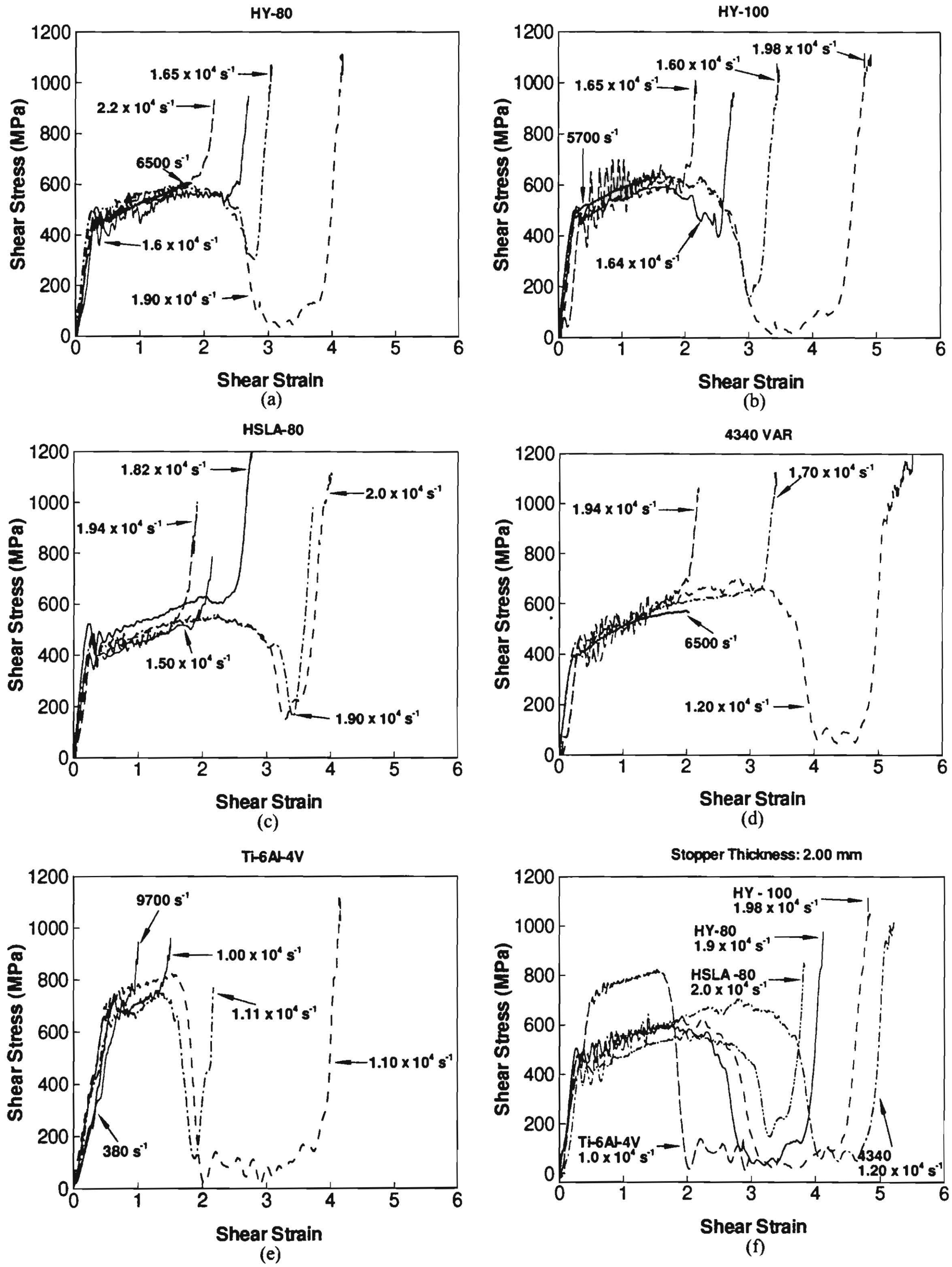

Fig. 4 Evolution of Stress-Carrying Capacity for Five Materials during Dynamic Shear Failure

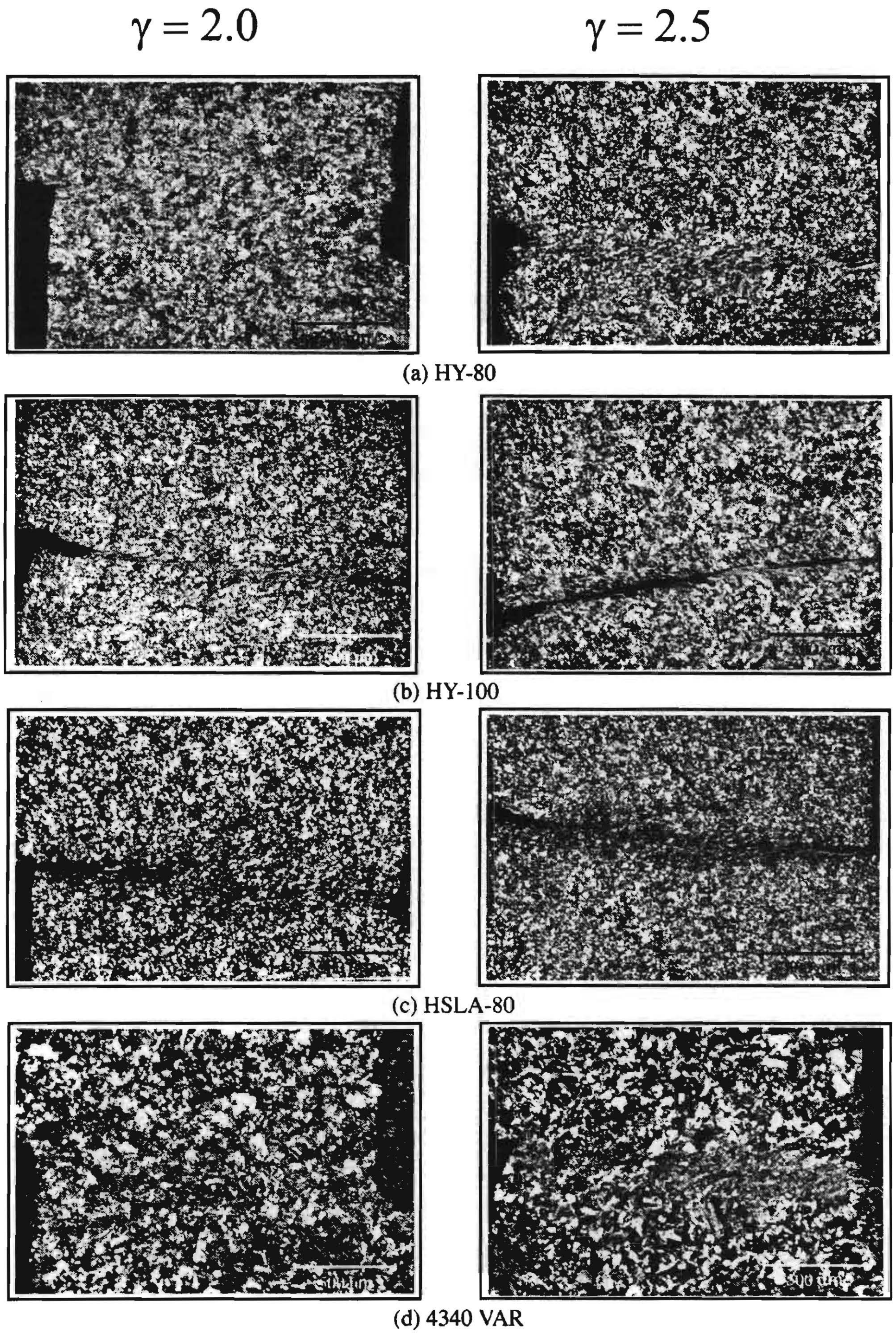

Fig. 5 Morphologies of Strain Localization and Ductile Rupture at γ =2.0 and 2.5 for HY-80,(b) HY-100, (c) HSLA-80, and (d) 4340VAR steels

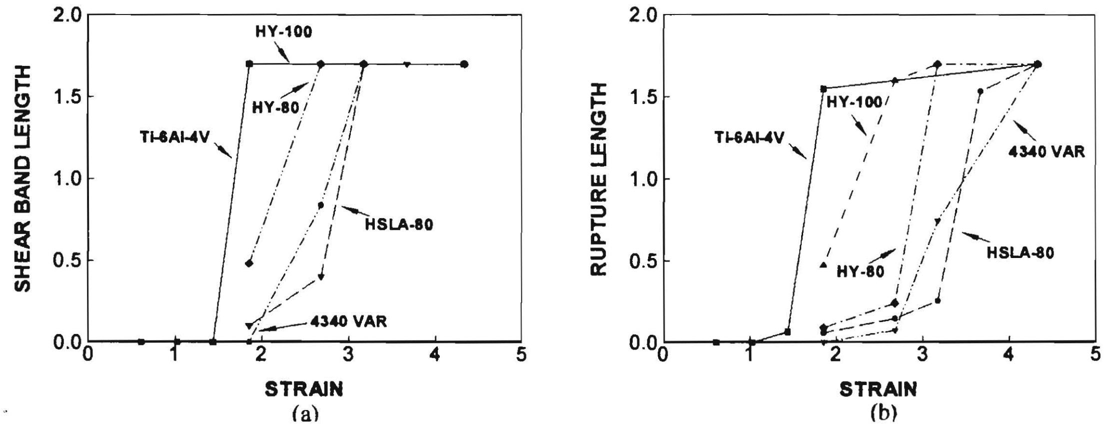

Fig. 6 Shear Band and Rupture Lengths as Functions of Shear Deformation
(a) Shear Band Length, (b) Rupture Length

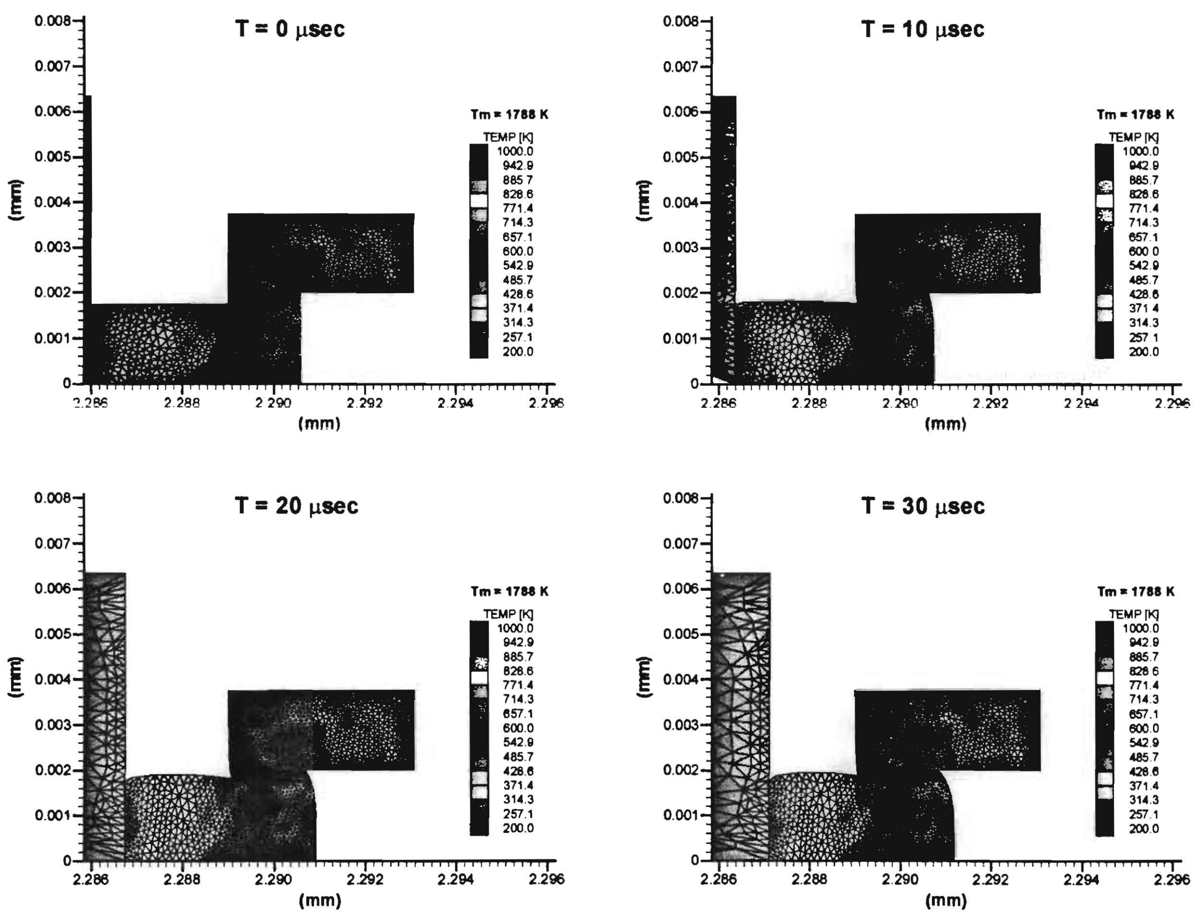

Fig. 7 Numerical simulations of the dynamic shear failure experiment
(Distribution of Temperature and Mesh Adaptation)

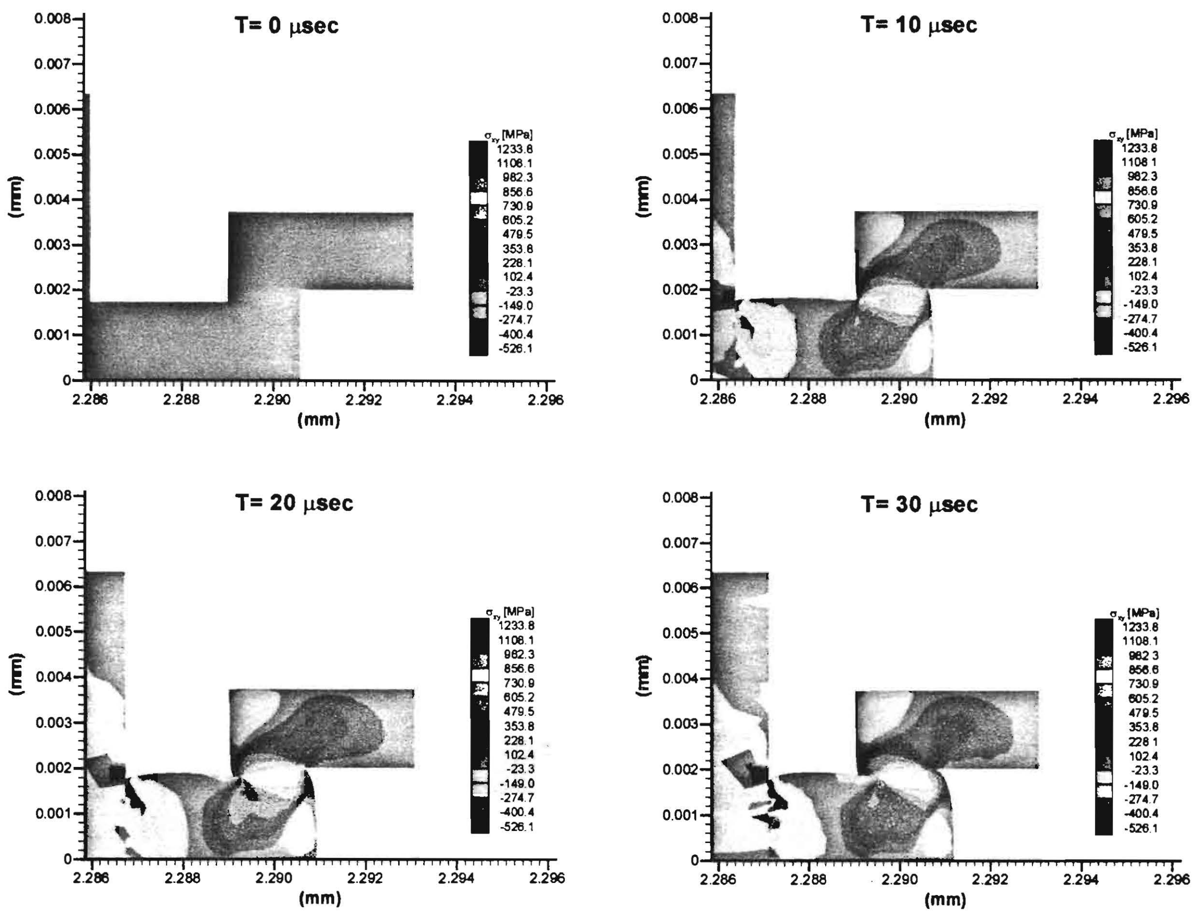

Fig. 8 Numerical simulations of the dynamic shear failure experiment
(Distribution of Shear Stress)

<u>*Cohesive Finite Element simulations:*</u>

Numerical simulations have been carried out using the CFEM approach developed, accounting for thermomechanical deformation and progressive rupture. The framework of analysis is fully dynamic and uses cohesive finite element to describe stress- and strain-controlled failure. Automatic mesh adaptation is used to resolve high gradient of deformation and arbitrary fracture paths. A series of deformation states during a calculation is shown in Fig. 7 and Fig. 8. These pictures show the stages of deformation, strain location, and rupture. The capability developed and the novel approach for complete account of ductile and brittle failure goes beyond the originally proposed scope of investigation.

The findings of this research are:

1) Despite their significantly different static properties such as yield strength and hardness, chemical compositions and heat treatment, the steels (HY-80, HY-100, HSLA-80, HSLA-100, and 4340) have very similar dynamic constitutive behaviors in the strain rate range of 10^2 - 10^4 s^{-1}.
2) There is a relatively large variation in the shear failure resistance among the steels, as measured by the stress strain curves and the critical shear strain for failure. This is in contrast to their similar thermomechanical constitute behaviors observed;

3) While the steels are also relatively rate-insensitive, the titanium alloy (Ti-6Al-4V) shows much stronger rate-sensitivity in the same strain rate regime. However, despite this higher rate-sensitivity, Ti-6Al-4V is more susceptible to shear banding and rupture than the steels. This finding is in contrast to the fact that strain rate dependence enhances resistance to shear localization;
4) Based on an approximate shear localization model of Grady (1994) which accounts for the strain sensitivity, thermal softening and heat conduction, very similar band dissipation energy (G_s) and shear band toughness (K_s) values are predicted for the steels, see Table 1. The toughness does not include the influence of microscopic damage and rupture inside shear bands on the stress-carrying capacity of materials. The significantly different shear failure behaviors of the steels observed demonstrate that rupture inside shear bands is an important part of the failure process that should to be considered in evaluating failure.
5) A Cohesive Finite Element approach has been developed allowing for full account of deformation and rupture. This provides a novel capability for quantifying the shear failure resistance of structural metals.

Table 1 Dissipation energy and shear band toughness

Material	Flow Stress (MPa)	Dissipation Energy Γ_s (KJ/m^2)	Shear Band Toughness K_s ($MPa\sqrt{m}$)
HY-80	1460	125.2	142.221
HY-100	1530	120.9	139.745
HSLA-80	1280	138.2	149.414
4340VAR	1450	125.9	142.588
Ti-6Al-4V	2000	3.935	18.861

Suggested Future Activities:

The cohesive finite element method developed allow simulation of both the deformation and failure processes in the metals. The actual experimental configuration should be accounted for as well as measured material properties. The modeling should provide full account for the effects of inertia, finite deformation kinematics, strain rate hardening, thermal softening and heat conduction. The novel capability will allow for a complete quantification of the factors influencing quantifying dynamic shear failure resistance of structural metals.

Relevance to the Navy:

This research is relevant to the design of naval structures in maximizing the structural integrity for various service conditions. This contribution is reflected in four ways: (1) the shear failure resistance comparison and shear failure toughness measure developed provides guidance for the selection of appropriate materials; (2) understanding of how shear failure propagates in materials will enable optimization of structural design to minimize damage; and (3) understanding gained will provide suggestion for the revision and improvement of naval structural metals and contribute to the development of more failure-resistant materials.

Refereed Publications:

1. M. Zhou, A. J. Rosakis and G. Ravichandran, Dynamically Propagating Shear Bands in Impact-loaded Prenotched plates, I - Experimental Investigations of Temperature Signatures and Propagation Speed, *J. Mech. Phys. Solids*, **44**, pp.981-1006, 1996.
2. M. Zhou, G. Ravichandran and A. J. Rosakis, Dynamically Propagating Shear Bands in Impact-loading Prenotched plates, II - Numerical Simulations, *J. Mech. Phys. Solids*, **44**, pp.1007-1032, 1996.

3. M. Zhou and R. J. Clifton, "Dynamic Ductile Rupture under the Conditions of Plan Strain, *Int. J. Impact Engng.*, **19**, pp.189-206, 1997.
4. M. Zhou, "Effects of Microstructure on the Resistance to Shear Localization for a Class of Metal Matrix Composites", *Fatigue and Fracture of Engineering Materials and Structures*, **21**, pp. 425-438, 1998.
5. M. Zhou and R. J. Clifton, "Dynamic Constitutive and Failure Behavior of a Two-phase Tungsten Composite", *Journal of Applied Mechanics*, **64**, pp. 487-494, 1997.
6. M. Zhou, A. J. Rosakis and G. Ravichandran, On the Growth of Shear Bands and Failure-Mode Transition in Prenotched Plates: A comparison of singly and doubly notched specimens, *Int. J. Plasticity*, **14**, pp.435-451, 1998.
19. M. Zhou, The Growth of Shear Bands in Composite Microstructures, *Int. J. Plasticity*, **14**, pp. 733-754, 1998.
7. K. Minnaar, Comparison and Analyses of the Dynamic Shear Failure Resistance of Structural Metals, M.S. Thesis, Georgia Institute of Technology, Nov. 1997;
8. K. Minnaar and M. Zhou, An Analysis of the Dynamic Shear Failure Resistance of Structural Metals, *J. Mech. Phys. Solids*, **48**, in press and to appear, 1998.
9. K. Minnaar and M. Zhou, Microstructural Failure Mechanisms during dynamic Shear Deformation of Structural Metals, manuscript in preparation and to be submitted to *Int. J. Plasticity*, 1998.
10. S. W. Park and M. Zhou, "Separation of Elastic Waves in Split Hopkinson Bars using One-point Strain Measurements", submitted to *Experimental Mechanics*, 1998.

Non-referred Publications:

1. S. W. Park, D. R. Veazie and M. Zhou, Characterization of Impact Damage and Residual Strength of Structural Composites, *Proceedings of the 12th ASCE Engineering Mechanics Conference*, pp. 1311-1314.
2. Minnaar, Comparison and analysis of Dynamic Shear Failure Behavior of Structural Metals, Georgia Tech M.S. thesis, 1997.

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13. ABSTRACT *(Maximum 200 words)*

The objective of this two-year research is to (1) characterize the dynamic constitutive behavior of structural metals including HY-80, HY-100, HSLA-80, HSLA-100, 4340 and Ti-6Al-4V; (2) evaluate the factors that determine their dynamic shear failure resistance; and (3) obtain experimental quantification of the failure resistance of these materials. A combined experimental and numerical approach has been employed in the investigation. The work carried out consists of experimental characterization of failure behavior and numerical simulations. Specific accomplishments are: (1) the responses of the above materials over a wide range of strain rate (of 10^{-3} to 10^{4} s^{-1}) have been characterized; (2) the dynamic shear failure resistances of these materials have been experimentally characterized; (3) a novel Cohesive Finite Element Method (CFEM) has been developed for the modeling of dynamic shear failure, accounting for microscopic rupture as well as thermomechanical response. Numerical simulations have been carried to illustrate the failure behavior and failure mechanisms. This accomplishment exceeded the initial scope of tasks.

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